DESIGN AND ANALYTICAL EVALUATION OF STAND-ALONE PHOTOVOLTAIC POWER SYSTEMS FOR RURAL AREAS IN THAILAND

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ABSTRACT

Rural Electrification is one of the main applications of photovoltaic (PV) power systems. Stand-alone PV generators are suitable for use in rural households or villages that are located far from the national utility grid because extension of the grid system into rural villages is expensive, especially in developing countries. PV systems are already cost-effective for rural electrification of scattered houses and villages. There are many rural villages in Thailand located without access to electric power. Rural people have used kerosene lamps and candles for lighting applications. There are no facilities for community entertainment.

This research project focuses on the design and analytical evaluation of stand-alone PV power systems for rural areas in Thailand. Both centralised and decentralised PV systems were examined. A sample village with 100 households in a rural area at Udon Thani Province of Thailand was selected for design of a centralised PV mini-grid system according to daily load requirement in the village. The daily electrical energy needs of a village can be broadly split into three categories, namely (i) for each household, (ii) for a community centre and (iii) for public use. The design of a centralised mini-grid system is detailed. The system sizing and prediction of system performance, especially the best matching between the array size and battery storage capacity, were carried out using a computer programme in C-language developed in this research. Other programmes were also specifically developed to analyse the following topics: (i) estimation of solar radiation on inclined surfaces for Thailand, (ii) design of electrical power distribution (mini-grid) system, (iii) lightning protection system and (iv) protective equipment sizing and conductor size.

One of the important parts of this research programme is the design of PV systems in decentralised applications. These are a battery charging station system, water pumping system, public lighting system, community facilities' system and solar home system. These topics consider how system size is determined, how specific system hardware is selected, what installations are good practice, and how the system's life cycle cost can be estimated. The worksheets are provided in an appendix for users as well as PV

engineers. Analytical comparisons of each PV system type in terms of system cost, possible benefits and problems for using in typical rural villages of Thailand have been addressed. Three PV applications for a Thai rural village, namely a mini-grid system, a battery charging system and a solar home system has been compared to determine the most advantageous. A strategic model for PV dissemination in Thailand has also been proposed emphasising the cost advantages of decentralised systems.

The results of this project are able to provide useful information for rural electrification planner and PV engineers to choose the optimum system for installation. They should be applicable in other countries with a similar climate and latitude angle.

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1.1 Aims of the Work

The aim of this research programme was the design and analytical evaluation of stand-alone photovoltaic (PV) power systems for rural areas in Thailand. Another objective was to make locally developed design knowledge accessible for wider application in a country which is in the early stages of PV dissemination, such as Thailand. A sample village with 100 households in Thailand was selected for the design of PV systems according to daily load requirement for electricity. The design focused on centralised PV mini-grid and decentralised PV systems for specific end-users. The designs assume the same load conditions and same village facilities for each system as well as the climatic data at the design location and system parameters.

The process of systematic analysis in some topics is complicated. As a result, computer programmes were specifically developed using C-language as a convenient and flexible tool for a specific design to ensure that the results are accurately calculated. The process of information dissemination is necessary for the successful implementation of a PV programme in developing countries. It is essential to consider the strategies for implementation of a PV project to ensure that it will be successful. This research work proposes a strategic model for PV dissemination in Thailand and discusses the roles of key players in the implementation of the strategy and the responsibilities of these organisations. The results of this research are able to provide useful information for rural electrification planners and PV engineers to choose the optimum system for installation in a rural villages in Thailand.

1.2 Context of the Work

Photovoltaic systems are playing an increasingly important role in developing countries and have the potential to become a major force for social and economic development. Access to electricity is a key element in determining quality of life. By most recent estimates, about two billion of the world's population have no access to modern forms of energy [1], particularly electricity where the costs associated with grid connections are very high. There is a need to look for alternative solutions to rural electrification. Decentralised power generation can provide some answers [1]. Many PV systems have been installed throughout the world, particularly in developing countries, for example for water pumping, vaccine refrigeration, household lighting and public lighting systems as well as a PV diesel generator with a mini-grid system [2-4]. Instead of separate PV kits in individual households, centralised PV systems or power stations have been installed in a number of villages in different parts of the developing countries and all over the world. Generally, these systems have outputs in the range of 10 to 30 kW_P. They have been usually designed to provide a 220 VAC supply through a village distribution grid. The power station itself consists of a large area of PV modules, a control room housing, power conditioning equipment, switching gears, battery storage bank and a back up diesel generator. In 1984, a 8 kW_P PV village power plant was operated at Utrick Island in the Marshall Islands. A PV power plant called ASHIA ROUMELI project in Greece has been installed with a capacity of 50 kW_P and the RONDULINU project in France has also been installed to operate in a village with a capacity of 65 kW_P [4]. In addition, many decentralised PV systems including solar home systems and PV battery charging stations are commonly installed in many rural villages.

Some the joint PV services are designed for specific programmes, for example World Health Organization (WHO) and UNICEF Expanded Programme of Immunisation (EPI) is the world's largest single primary health care programme. A specific service is refrigeration of vaccines in its rural health clinics. In 1985, the EPI decided to adopt PV powered refrigerators wherever they were economically and technically justified. About 3,000 PV refrigerator have been installed through the developing countries, and around half of them in Africa. The operating principle of PV refrigerators is similar to that of normal domestic electricity powered models except that they operate at 12 or 24 VDC rather than 220 VAC. They have more insulation than domestic refrigerators to reduce energy use. Energy consumption figure ranges from as little as 0.15 kWh a day up to 1.0 kWh, depending on the refrigerator size, the operating conditions, and whether a freezer compartment is included. A fairly typical figure is about 0.3 kWh a day when an average ambient temperature is about 32°C. Nevertheless, the requirements for vaccine refrigeration are rigorous. Most vaccines must be kept within a temperature range of 0° to 8°C to retain their efficiency, in both cases, the vaccine is rendered ineffective. Refrigerators used for vaccine storage must meet the performance requirements with a reasonable margin of safety.

The development of PV pumps was pioneered in France [5]. The first systems used a Pompes Guinard motor-pump comprising a surface-mounted permanent magnet DC motor driving a submersed centrifugal pump by a vertical shaft. The motor was connected directly to the PV array. In 1978, a team at the World Bank presented a case for a programme to apply PV pumping systems for irrigation on a large scale. As a result, the United Nations Development Programme (UNDP) provided funding for the Global Solar Pumping Project, executed by the World Bank. Consultants were appointed by the World Bank to evaluate, test and demonstrate commercially available small-scale solar powered irrigation pumping systems. At the time, the technical feasibility of solar powered pumping had been demonstrated in a limited way, but the technology was immature and expensive. The purpose of the project was to advise the UNDP and the World Bank on how solar pumps should be developed. They decided to continue the work to the point where very widespread demonstration could be contemplated. The activities included an assessment of prospective countries for participation and procurement of improved commercial systems and sub-systems for testing to qualify them. According to the economic feasibility studies, PV pumps were broadly competitive with the primary alternatives and could be justified in many regions where diesel costs are high, wind speed low and a steady year round demand for water exists. It was shown that village water supply would in general become economic before irrigation. PV pumps have, over the past decade, evolved to be stable and reliable. A total of more than 10,000 has been installed to date [5], of which 30-40% are in developing countries. In Zimbabwe, 15 pumping systems were installed to provide water supplies for the villages and local schools. The project will also carry out cost comparisons with other water supply options. The first PV pumping systems was installed in 1993 [5], and six systems and the rest of the total systems were also installed in the following years. The local private sectors have been involved in the installation, maintenance and monitoring of the systems.

Household PV electrification in the villages is typically suitable for rural households located far from the national utility grid. Over the past decade, solar home systems in remote communities have increasingly received attention as an economically viable alternative to grid connections, kerosene lighting and rechargeable or disposable batteries that power all appliances. Government, non-governmental organisations (NGOs), the private sector and the donor community have acquired considerable experience in the design and implementation of solar home projects. Early solar home system performances met with a variety of difficulties. These included unreliable technical performance, organisational and cost recovery problems and users' dissatisfaction resulting from unrealised expectations. More recent projects in some developing countries utilising improved systems have incorporated lessons learned from these experiences and are performing quite well.

Thailand is now in the early stages of PV dissemination. The main PV rural applications in Thailand have been battery charging, telecommunications and water pumping systems. This research has looked at the PV systems that is most appropriate for Thailand and has also looked at a suitably strategic model for PV dissemination in Thailand for the future.

1.3 Organisation of the thesis

The organisation of the thesis is broadly divided into 3 parts as follows:

(i) ***general information***

It describes the energy resources, photovoltaic (PV) applications and rural electrification in Thailand including an overview of PV technologies and systems.

(ii) ***methodologies, analysis and results***

This part discusses the design of stand-alone PV power systems as well as the economic analysis of PV systems

(iii) ***proposition, comparison and final conclusion***

It defines the PV dissemination, proposes a strategic model of PV dissemination (case study in Thailand) and final conclusions of the thesis.

The subsequent chapters of the thesis are shown in Figure 1.1

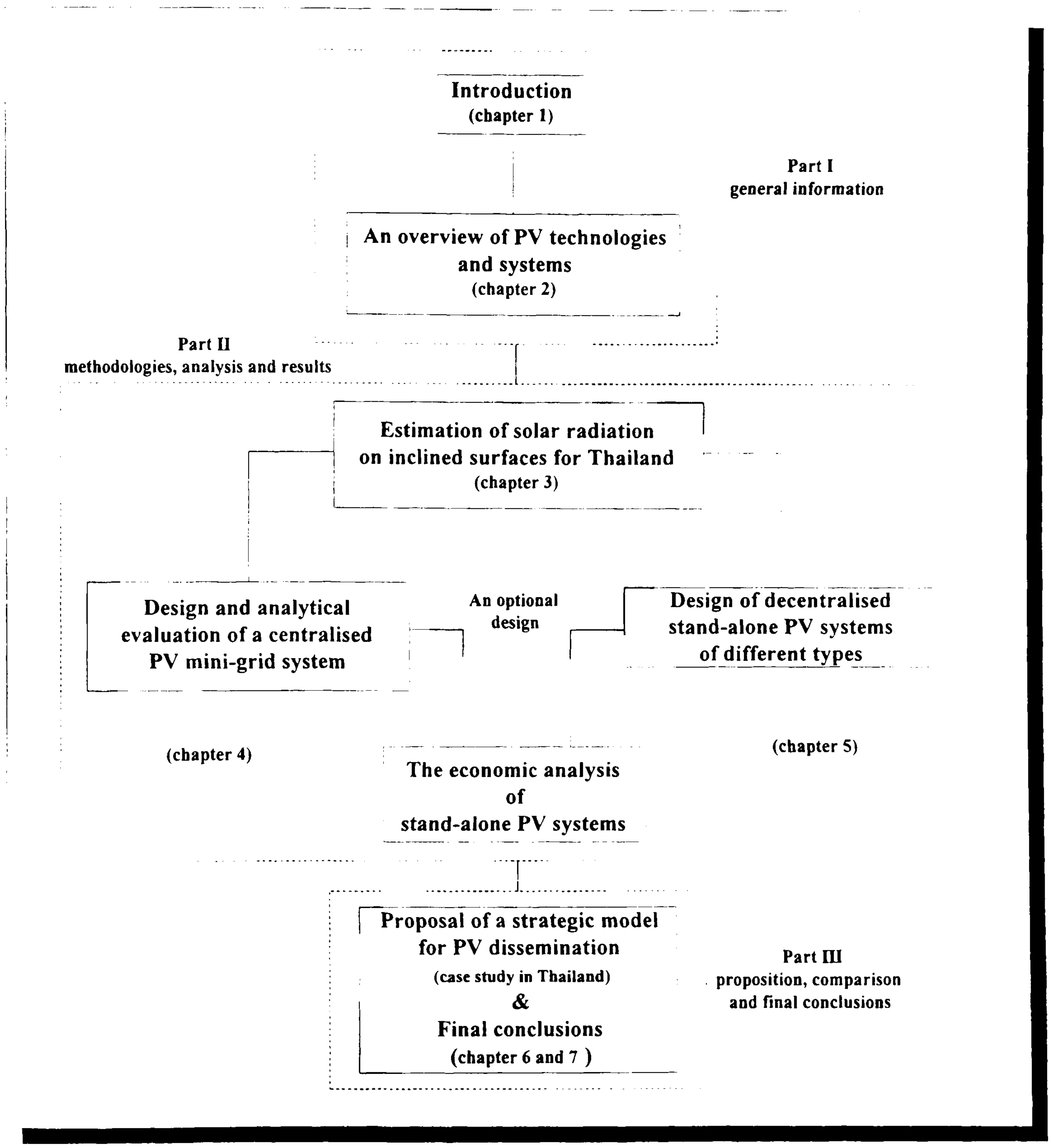

Figure 1.1 Organisation of the thesis

1.4 Geography of Thailand

Thailand is situated in the heart of Southeast Asia with Bangkok as the capital city. It is also situated approximately latitude between 6° and 20° N, and longitude between

97.5° and 105.5° E. Thailand covers a land area of 198,114 square miles [6]. it is about the size of France and has a population of 62 million (in 1999). It is approximately measured 1,553 miles from north to south and 776 miles from east to west. Furthermore, it has 1,143 miles on the Gulf of Thailand and 528 miles on the Indian Ocean. Thailand is bordered to the west and north by Myanmar (Burma). to the north-east by Laos, to the south-east by Cambodia and to the south by Malaysia. The isthmus is shared with Myanmar that gives Thailand a short coastline on the Indian Ocean, and the county also has a long Pacific coastline on the Gulf of Thailand. The climate is tropical and humid, with an average annual temperature of 29°C (85°F). The solar radiation climate of Thailand can be generally stated that [7] during the Spring (February-April), the weather is fine and the whole of the country has from 8 to 9 hours of sunshine per day. This is the season of maximum insolation. In summer (May-July), the duration of sunshine is about 5 to 7 hours per day. During the autumn (August-October), the duration of sunshine is about 5 to 6 hours per day in many areas. This is the period of heavy rain and the lowest insolation of the year. In the winter (November-January), the weather is fine and there is about 8 to 9 hours of sunshine per day over the most of the country.

There are five broad geographical regions in Thailand. The North of Thailand is the largest region. It is a mountainous region with narrow river valleys and supports most of the minority hilltribes. The northeastern part is the second largest region and is an arid area characterised by a rolling surface and undulating hills. Harsh climate conditions often result in this region being subjected to flood and drought. The eastern region contains the famous seashores and beautiful islands. Central Thailand, the basin of the Chao Phraya River, is a lush, fertile valley. It is the richest and most extensive rice-producing area in the country and has often been called the "Rice Bowl of Asia". This is the heart of Thailand, the region where the original Thai first settled, attracted here by the extra-ordinarily fertile soil. The southern region is hilly with thick virgin forests and rich deposits of minerals and ores. This region is the centre for the production of rubber and the cultivation of other tropical crops apart from being geographically different from the rest of Thailand. The South has its own economic, ethnic and political features. It is sandwiched by the Andaman Sea and the Gulf of

Thailand, is lined with sandy beaches and palm-fringed islands lying just offshore. Some of the finest beaches in the country can be found in this region, while inland are mountainous scenery, caves, waterfalls and jungle.

1.5 Energy Resources in Thailand

There are two main types of energy resources in Thailand that can be usefully applied and have been developed. They are as follows:

1.5.1 Natural Resources

1.5.1.1 Natural Gas and Oil

The potential for natural gas and oil in Thailand is quite substantial. Proven and ultimately recoverable reserves of natural gas and oil have been found to be 348 m^3/day and 513 m^3/day respectively. In 1985, natural gas productions from the Gulf of Thailand were about 6.8 million m^3/day. Current production from the Sirikit oil field in Kamphaengpet province is about 20,000 barrels per day. New oil fields were recently found off the Bang Rakam District and Chumporn province, and they are estimated to produce about 10,000 barrels per day. In addition, more gas and oil fields are expected to be found, both off and onshore. In 1996, Thailand produced 1,270 million cubic feet per day (mcfd) of natural gas and 35,736 barrels per day (bpd) of condensate [8]. Unocal Thailand Ltd., and its partners produced gas and condensate at an average rate of 808 mcfd and 27,950 bpd respectively [9] from their 11 fields in the Gulf of Thailand. The gas industry in Thailand is virtually dominated by two players, the Petroleum Authority of Thailand (PTT) and the Electric Generating Authority of Thailand (EGAT).

1.5.1.2 Lignite

Lignite deposits have been found in 37 basins in northern and southern provinces of Thailand. Present proven reserves are about 1,100 million tons with over 80% are located in the north. Recently, large lignite deposits have been identified at Songkhla province in the southern part with a reserve of over 100 million tons. Surat Thani province that is also situated in the southern part with reserves of about 150 million tons. At present, industrial uses of lignite occur mainly in the cement industry and in small and medium size factories around Bangkok. However, whilst the standard of air quality that exists in Thailand, emission regulation for lignite combustion has not been established yet. Boilers used in power stations and industries emit sulphur dioxide directly into the atmosphere. Increasing use of domestic lignite and imported coal for electrical generation and industry has led to discussions on better pollution control.

1.5.1.3 Oil Shale

Exploration of oil shale in Thailand has existed in the northern part of the country since 1935. Approximately 21,000 million tons of oil shale have been identified with a shale oil reserve of about 6,700 million barrels. Recoverable reserves are estimated at about 2,400 million barrels. The kerosene content in Thai oil shale is relatively low, below 10% on an average. Though several processes for shale oil extraction have been mainly developed in U.S.A, at current level of oil prices (US$ 15 per barrel) the exploitation of shale oil in Thailand would not be competitive. The oil shale reserves represent a large domestic source of energy for the future.

1.5.2 Renewable Resources

1.5.2.1 Hydro-Electricity

Hydro potential exists and can be further utilised when environmental issues are resolved. As part of the rural electrification programmes to bring electricity to 95% of all villages by 1990, 29 small hydro-electric plants have been identified as economically suitable for more accurate cost estimates and detailed engineering work. At some sites feasibility studies of a small hydropower project tends to indicate that the cost of electricity generated can be more cheaper than electricity generated from a diesel electric set on a PV plant [10]. Kendal-based Gilkes Ltd., has supplied three Turgo Impulse turbines for two projects, Nam Man and Nam San, in Northern Thailand. The projects were designed and managed by Balfour Beatty Projects & Engineering Ltd., for the Provincial Electricity Authority of Thailand. The Nam San station has two 3 MW turbines generating sets operating on a net head of 85 m (at a 375 rpm) and the Nam Man station has one 5 MW set operation on the net head of

119 m (at 429 rpm) [10]. At present, a total capacity of 73 MW of small hydroplants (200 kW to 6 MW) and micro hydroplants (<200 kW) have been installed [11], of which micro-hydro corresponds to only 2.3 MW. There are 73 micro-hydro projects completed in the country and two projects with a total capacity of 9.95 MW are under construction [12].

1.5.2.2 Biomass

In 1985, rural households using wood and charcoal for cooking were about 54% and 46% respectively. The total sustainable supply of fuel from wood in 1983 was estimated at 15.5 million cubic metres per day (mcmpd), but the total consumption of fuel from wood in the same year was about 38.6 mcmpd. The deficit of 23.1 mcmpd was met by over cutting of forests. By 2001, potential demand of fuel from wood could reach up to 30 mcmpd. To avoid serious environmental and economic damage, reforestation programmes have been implemented. During the last five years, about 100,000 acres of eucalyptus have been planted and large plantations of other fast growing trees are planned by both public and private sectors. Several agricultural residues have been used as fuels in rural industries. Most of the bagasses resource, estimated at 7.5 million tons per year, is used as boiler fuel in sugar mills. Rice husk supply was estimated in 1987 to be over 5 million tons, 40% of which was used as boiler fuel in rice mills [12]. More than 3 million tons are still available as energy resource for rural industries or electricity generation whose potential is estimated to be at least 88 GWh per year. Palm oil wastes consist of fibre, shells and empty bunches are used as boiler fuel in palm oil mills. Other agricultural residues such as straw, maize stalks, cassava stalks, coconut shells and hush also have potential as energy resources for rural areas with a total supply of about 35 million tons per year. Some types of industrial waste water can be utilised for biogas production. Laboratory scale tests were conducted on several types such as tapioca waste, canning food waste and dairy waste in order to determine their potential. A pilot study of biogas production from pineapple waste has been successfully conducted and an industrial plant is under construction at a pineapple canning factory. Several breweries in Thailand have generated biogas from their wastes. Liquid waste from sugar mills and palm oil mills are also being considered for biogas generation. Nowadays, Thailand has made significant progress in implementing three biomass technologies (i.e. biomass-fired electric power plants, biogas plants and improved cook-stoves) and about 229 MW (include waste-fired power plant) of biomass based power plants have already been constructed [11,12].

1.5.2.3 Solar Energy

Thailand is a country with abundant sunshine, and solar systems can be applied throughout those rural areas. The highest mean values of solar radiation are 5.42 $kWh.m^{-2}.d^{-1}$ in spring and the lowest values are below 4.12 $kWh.m^{-2}.d^{-1}$ in restricted localities with heavy rainfall in autumn. Rough estimates of diffuse solar radiation and atmospheric turbidity are made from the radiation sunshine regression parameters. Diffuse radiation averages 2.33 $kWh.m^{-2}.d^{-1}$ and the annual average solar radiation is approximately 4.70 $kWh.m^{-2}.d^{-1}$ [7,13]. However, solar energy has been used non-commercially in the country for centuries. Its use in salt production from sea water has been estimated to be as much as the equivalent of 20 million barrels of oil. Sun drying of some 15 million tons of paddy rice per year requires solar energy that is equivalent to about half a million barrel of oil. Sun drying has also been widely used for other agricultural and marine products. A solar water heating industry has been established in Thailand for almost a decade with solar collectors installed in hospitals, hotels and private homes. Current domestic production of solar collectors is over 10,000 square meters per year. Development of solar dryers has been very active and a few designs of convection dryers have been commercialised. Several designs of solar stills have been developed including vertical surface solar stills, and installation of large solar stills for demonstration is being planned. Generation of electricity by PV cells has been rapidly developed in Thailand. A large number of demonstration projects for telecommunication, lighting and water pumping have been set up with a combined peak output of 400 kW_P. PV modules are locally produced in a few factories. Thailand has already installed solar thermal systems with a total collector area of 50,000 square metres [11].

1.5.2.4 Wind Energy

Generally, the potential of wind energy in Thailand is not promising as the average wind speed in the country is about 2 m/s [13], quite low for economical utilisation. Estimates of mean power densities of surface wind over the whole country are typically in the range 10-20 W/m^2 [14]. Upper level climatic charts indicate that the mean free-stream wind power densities above the surface boundary layer are typically in the range 100-600 W/m^2. Sufficient power densities would be accessible to wind machines on high ground, depending on mountain topography and machine siting. The air over Southeast Asia has its origin in the trade winds from the Pacific Ocean during February to May. The prevailing winds over Northeast Thailand and the peninsula are from the East. In Central Thailand, the solar heating of the land mass and the north-south orientation of the mountain chains on the Thai-Myanmar border make the air flow northward so that southerly winds prevail. The wet southwest monsoon from the Indian Ocean covers the whole area from June to September. The tropical convergence zone moves southward over the country during September and October, and by November northeasterly winds are established in most places. These northeasterly winds persist through the winter, and surges of cold air from China occur from time to time in December and January. In spite of that, high wind speeds exist in some coastal areas and windmills have been used for water pumping in salt farms and rice fields in Samut Sakhon, Chonburi and other provinces. It has been shown that traditional sail-type windmills used for water pumping in salt farms are more economical than diesel-driven water pumping [14]. Demonstrations of wind electric power systems have also been conducted. In Thailand, wind turbines with a total capacity of 200 kW are mainly used for water pumping in remote areas. Electricity generation is also possible in the islands of the southern region where the wind velocity is higher.

1.5.2.5 Geothermal Energy

Geothermal resources occur throughout the world and are particularly abundant in many developing countries, where their utilisation can displace the development of polluting fossil-fuel-fired power stations. At present, about 0.3 MW of geothermal electrical power generation is on line in Thailand [15]. The applications of geothermal energy in Thailand have been conducted since 1946 and more than 90 hot springs, with temperature ranging from 40°-100°C, have also been mapped.

At San Kampaeng district, EGAT and JICA initiated a technical cooperation project in 1981. Exploration surveys were conducted from 1982 to 1989 and two deep wells were completed in 1989. The wells failed to yield enough data to characterise the deep reservoir. However, a well, GTE-8, produced 40 tons/hour of 125°C water from a fracture at a depth of 920 metres. Further work at San Kampaeng has been suspended pending the development of directional drilling techniques that can economically test the vertical fractures through the reservoir conduit system. Thai geothermists believe that San Kampaeng district has the potential to produce about 5 MW of power, but development awaits the availability of cooling water and lower cost drilling techniques. Pre-feasibility studies at Pai district were scheduled by EGAT for 1994 to 1995. Preliminary studies indicated that the area was similar to Fang district with geothermometric temperatures of 140°-180°C.

1.6 PV Applications in Thailand

Thailand is a country with abundant sunshine, and stand-alone PV systems can be applied throughout those rural areas located far from the national utility grid. PV systems in Thailand have been applied nationwide since 1976. In the first period, the PV systems were installed at health care centres in remote villages by the Ministry of Public Health. Later projects included battery charging stations, water pumping, communication repeater stations, lighting for households in typical rural areas [16]. The total installed capacity of PV systems is approximately 7 MW_P. At the end of 1996 [the last year of the 7th National Social and Economic Development Plan (1992-1996)], the most common PV applications were PV battery charging stations and PV water pumping systems. There were 785 villages in various provinces that used electrical power from PV power plants, with 942.5 kW_P of PV battery charging stations [17]. The majority of PV battery charging stations were installed in the northern part of Thailand. PV pumping systems were installed mainly in the northeastern part of Thailand, where a total of 490.9 kW_P has been installed. Considering all the provinces of the country, PV water pumping systems have been installed in a total of 619 villages with a total installed power of 580 kW_P. By 1991, the cumulative installed power was 500 kW_P but by the end of 1996, 2.5 MW_P of PV systems were installed. The peak power installed up to the end of 1997 for PV systems for various applications is shown in Figure 1.2.

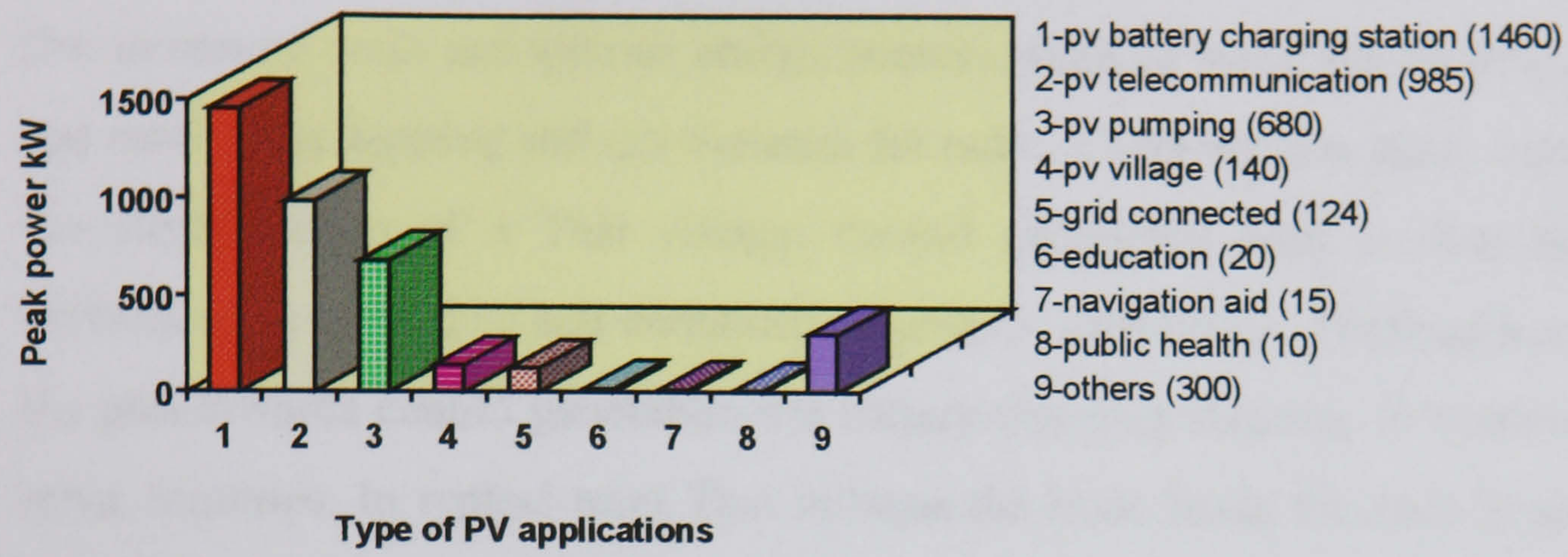

Figure 1.2 Peak power (kW_P) of PV systems installed in Thailand for various PV applications by the end of 1997 [18].

As can be seen from Figure 1.2, PV battery charging stations were the major application of PV systems in Thailand, followed by telecommunication systems. The total power of PV systems installed by the end of 1997 was approximately 3.73 MW_P. The National Energy Policy Office (NEPO) of Thailand has a policy in which 20 MW_P of PV systems will be installed from now until the end of the 9th National Social and Economic Development Plan (1997-2006) [19].

1.7 PV Rural Electrification

Rural electrification is a development priority for many countries, on the grounds of social equity, economic development and a counter to the population drift from country to city. Rural electrification is also a major infrastructure programme of the Thai Government. It aims to accelerate socioeconomic development in remote areas by providing new and better opportunities for increasing income, facilitating communication and mobility as well as improving the general awareness and self reliance of people. In general, rural people have a low income because the rural economy is a subsistence economy. Progress in rural development will depend on the provision of infrastructure such as roads, water supply, health service and education. Electricity is a major facilitating factor in the provision of these other infrastructures. The domestic electricity needs for a reasonable quality of life for families in typical rural areas is approximately 0.5 kWh per person per day [20]. This estimate is valid for many remote areas of developing countries. Typical rural people in Thailand who live in remote areas use various energy sources, such as wood for cooking, kerosene and candles for lighting and dry batteries for radio. There are two basic approaches to the electrification of a Thai village: central generation with a local distribution network or an individual self-contained system for each house. Thailand has tended in the past towards central generation via battery charging stations, in contrast to most other countries. In typical rural Thai villages the basic loads for each household are lighting and radio. The loads for public use are water pumping and street lighting. A school in the village would need lights and a TV set with a video recorder, while a medical centre needs the lighting and a vaccine refrigerator. The main PV applications in Thailand have been battery charging, telecommunications and water pumping systems. Thailand differs from neighbouring countries in promoting village battery charging rather than solar home systems, although this seems likely to change in the next 5 year plan.

Battery Charging Stations : Two Thai Government programmes for the installation of PV battery charging stations in rural areas have been implemented since 1987. Firstly, the Department of Public Works under the Ministry of Interior installed systems in approximately 100 villages. Secondly, the Department of Energy Development also installed PV battery charging stations in a range of rural villages. There have also been some international programmes in Thailand which funded the installation of centralised PV battery charging stations. The Japanese New Energy Development and Industrial Technology Organization (NEDO) has installed such systems at 2 sites in remote areas since 1992. A 4 kW prototype system for 16 batteries was installed in the western part of Thailand, and a 40 kW demonstration system for 500 homes was also installed in the southern part of the country. The PV system, which is located centrally to four adjacent villages, began operation in

February 1995. Staff supplied by the Thai Government are stationed there to manage and maintain the system, and can supply information to the users.

A nationwide survey of problems with PV battery charging stations in various provinces of Thailand has been carried out since 1997 as part of the 8th National Plan (1997-2001) and a variety of problems have been reported [18]. Most of the problems are technical, such as charge controller problems. For instance, batteries which cannot accept a full charge because they were left in a low state of charge for a long period have been further harmed by overcharging with subsequent water loss. It is clear that a low-voltage cut-off needs to be installed with each battery to protect it from over-discharge. Amongst other problems, it has been found that PV battery charging stations may be in operation for only 3-4 years in a village before a grid extension is provided. When this happens, most people changed their appliances from DC to AC, making the PV battery charging stations redundant. In order to avoid the waste of the PV system, it must be transferred to another location and re-used. This could take the form of i) re-installation of the battery charging station at the new location, ii) adding power to an existing PV system, iii) using the PV modules for another purpose such as providing power for a community centre. A further problem has been the scarcity of skilled maintenance personnel. If the system failed, the waiting time for repair was long and this caused disillusionment amongst the villagers and a reluctance to use the PV station after repair. Since skilled man-power is so scarce in remote areas, any systems having other than very simple operating or maintenance requirements are generally unsuccessful.

Water Pumping System : PV pumping systems have been installed in many rural Thai villages by the Department of Civil Works (DCW), part of the Ministry of Interior, which is the principle agency responsible for PV pumping systems in Thailand. As previously mentioned, over 619 PV pumping systems have been installed in Thailand with a cumulative power of approximately 580 kW_P. About 74% of the total PV pumping systems were installed by DCW. Another programme, named the Green Esarn Project, was carried out by the Ministry of Defence from 1988 to 1992, as a special project for the development of the northeastern part of Thailand. Studies have been made of problems with PV pumping systems in various provinces of Thailand [17,21]. The main problem is high sediment in water, followed by motor/pump failure. A typical PV pumping systems consists of 16 modules (BP Solar 1255 HP) with 8 in series and 2 rows in parallel (880W_P), a 3 phase inverter (SA 1500 Grundfos) and motor 550W (SP 5A-7 Grundfos) [22]. The volume of water pumped has been typically between 20 and 30 m^3/day. Field experience has shown that the systems are reliable in themselves, but the problems of silt in the water input must be taken into account in the design if long life is to be achieved. The users in the villages seem to be satisfied by their improved water supply. It is clear that the provision of clean drinking water is an important application for PV pumps. Impure drinking water is responsible for a large fraction of the illness and infant mortality in most rural areas, so the provision of clean water is a major social benefit.

Rural Telecommunications : PV-powered telecommunication systems are used in various rural areas of Thailand and the installed power is now approximately 985 kW_P. The Telephone Organization of Thailand (TOT) is the major organisation responsible for the installation of PV telecommunication systems. The most common are communication repeaters, radio transceivers, radio telephone links, radio receivers and community television. In 1983, the World Bank funded the installation of 51 PV powered telephone repeater stations throughout Thailand, with capacities among 1.3 and 4.1 kW_P [23]. In addition, the Electric Generating Authority of Thailand (EGAT) and the Ministry of Defence have set up PV telecommunication systems in rural areas with a total installed power of more than 20 kW_P.

The three main PV applications in Thailand discussed above are commonly used throughout the rural areas. There are other PV applications that could be of benefit in Thailand, and that can be used in all areas, such as transport aids, electrified cattle fencing and corrosion protection systems. In many countries, PV has become well established for powering transport aids such as railway crossing lights and signalling, runway lights, tunnel lights and emergency telephones [24]. In addition, PV powered electric fence systems are used widely in some countries. These PV systems could be used and would help to promote the development of PV in Thailand.

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Chapter 2

An Overview of Photovoltaic Technologies and Systems

Chapter 2

2.1 The Need for Photovoltaic (PV) Energy Conversion

Renewable energy will have to play a crucial role in the future energy supply of the world because of limited reserves of both fossil and nuclear fuels. Among potential new energy sources, the direct PV conversion of sunlight into electricity, is extremely promising. Solar cells can supply energy to systems with power varying from a milliwatt up to megawatt level. They are reliable, static and low maintenance. There are three main reasons for the general worldwide interest and research investment in PV [1].

Firstly, its long-term energy potential is enormous. Almost everywhere on earth a typical house roof covered in solar cells captures enough solar energy to completely supply its electrical load, provided that enough storage is installed. Secondly, by most recent estimates, about two billion of the world's population have no access to modern forms of energy, such as electricity [2]. The majority of these people depend on burning biomass, dung or waste from agriculture for cooking, heating and lighting, and on human or animal power for tasks such as grinding and transport. The time spent on collecting wood or hand grinding corn takes away time that could otherwise be used for income-generating activities. In addition, lack of suitable lighting will limit the time available for children to study after school, so limiting educational development. Such traditional sources of energy also have implications for health. Cooking indoors on an open fire, as humans do in poor households of developing countries, can cause serious respiratory and eye problems for the women, and the young children who stay near them [3]. Because of the modern image of electricity, its convenience and its cleanness, it is not surprising that rural electrification is a highly political issue in most developing countries. Solar electricity is a very attractive approach as it makes possible stand-alone systems that are fuel free and highly reliable. Now in the year 2000, about 40% of the world population will live in the villages in developing countries where decentralised electricity generation is necessary. Photovoltaics can be mutually beneficial for commercial contacts between the industrialised and the Third World, including technology transfer and the starting up of a local industry in the developing countries. Thirdly, PV makes use of semiconductors and, from the viewpoint of materials and of processing technology, is related to microelectronics. Research in PV, therefore, can also yield results useful for the microelectronics industry. A typical sample is the introduction of new semiconductor materials. The long-term outlook for PV is excellent, bearing in mind the predicted price decrease. Furthermore, a final reason why one should not expect a strong contribution of PV to world energy production within the next 20 years is the fact that the large scale introduction of a technology normally takes more than 40 years. However, it is essential that intensive research efforts should be continued, causing the cost reduction of an order of magnitude. That is necessary for PV to become competitive with other energy technologies for large scale production of electricity.

2.2 Photovoltaic Technologies

PV cells have been developed to directly convert sunlight by transforming photons of light into electricity. Cells capable of performing this function are connected together and packaged into modules capable of generating several watts of electricity. Modules are connected to generate larger quantities of electricity using only the sun as the future source. Although PV has proved to be largely reliable and durable under extreme conditions, a number of refinements, mainly to the complete system as opposed to the modules themselves, is still needed before PV systems will be appropriate for use in developing countries. Although system reliability is a cause of concern, another worry concerns the high cost of PV. Costs will fall sharply when techniques of mass production are introduced, but the cost of PV electricity also depends heavily on reducing the high cost of such low technology problems as weatherproofing cells and mounting them in the field [4]. A number of strategies for reducing PV system costs are being actively pursued around the world. The most promising seem to be methods for depositing thin layers of material on glass substrates, and methods using low cost optical systems to concentrate sunlight onto comparatively small, high-efficiency cells.

Most PV cells that generate electricity consist of a module of silicon wafers from crystal block connected together. Typically, each cell has a diameter of approximately 10 cm and can generate about one watt or more of electricity [5]. When they are connected together into a module, more electrical power will be generated. By connecting many modules together into the arrays, it is possible to generate many kilowatts or even megawatts from a PV generator. PV modules are rated in peak Watts (W_P). This is a reference value of the maximum power output from the module when operating under the standard test conditions. In fact, they are tested under the following conditions [6-9] ; (i) 1,000 W/m^2 (or 850 W/m^2 for concentrators) for irradiance, (ii) air mass (AM) 1.5 for spectrum of light, (iii) 25°C for the cell temperature. In the developing world, it is usually impractical, and indeed extremely expensive, to generate more than a few kW from PV generators. As a result, most uses for PV arrays are for powering low demand electrical appliances. Although the PV effect has been recognized since 1839, practical application began in the early 1970s, when PV cells were adopted by the U.S. space programme. In 1990, worldwide photovoltaics sales reached 153 megawatts [10], with Japan having the largest growth. In fact, over 80% of the growth from 1997-1998 (72% in two years) was due to the heavily subsidized Japanese grid-connected residential programme.

2.3 The Photovoltaic Effect

The PV effect is the basic physical process through which a PV cell converts sunlight into electricity. Actually, light (not just sunlight) consists of photons. For sunlight, these can be considered as "packets of solar energy". These photons contain different amounts of energy that correspond to the different wavelengths of the solar spectrum. When photons strike a PV cell, they may be reflected or absorbed, or they may pass right through. The absorbed photons generate electricity [11-14]. The energy of a photon is transferred to an electron in an atom of the semiconductor device. With its newfound energy, the electron is able to escape from its normal position associated with a single atom in the semiconductor to become part of the current in an electrical circuit. Special electrical properties of the PV cell provide the voltage to drive the current through an external load.

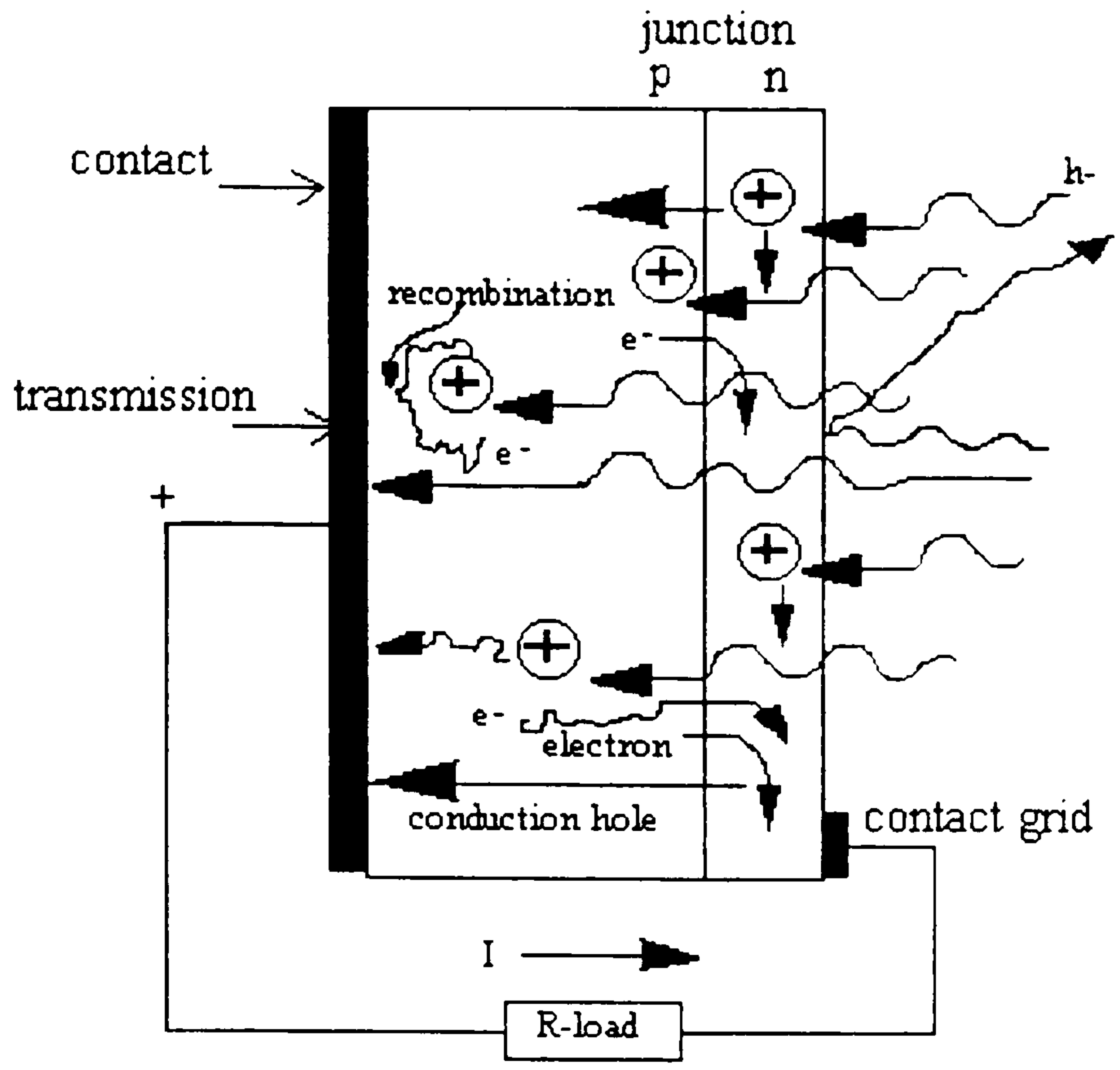

Figure 2.1 Photovoltaic cell and current flows [15]

As can be seen from Figure 2.1, photons or packets of light falling on the cell with sufficient energy will generate hole-electron pairs. Those outside the influence of the electric potential of the junction recombine while those within are separated. Electrons in n-type portion diffuse across the p-n junction into the p-type region, and holes, likewise, diffuse across the junction into the n-type region. Hence, a permanent electric field is established in the region of the junction. Silicon at room temperature has a band-gap of about 1.08 eV (i.e. the energy required to generate a hole-electron pair) [15]. Photons of light having energy in excess of 1.08 eV are capable of generating these electron-hole pairs in silicon. With no light incident on the active face, the cell exhibits the normal reverse bias characteristic of a p-n junction diode. To generate electricity, contacts are made on each either side of the cell, and, when an external circuit is connected to an illuminated cell, the intrinsic junction potential gradient drives the photon generated electrons around the external circuit and can be made to do work [16]. The cell is covered with a thin layer of dielectric material, the antireflection coating (ARC), made with layers of silicon monoxide to reduce reflection of light from the top surface of the cell.

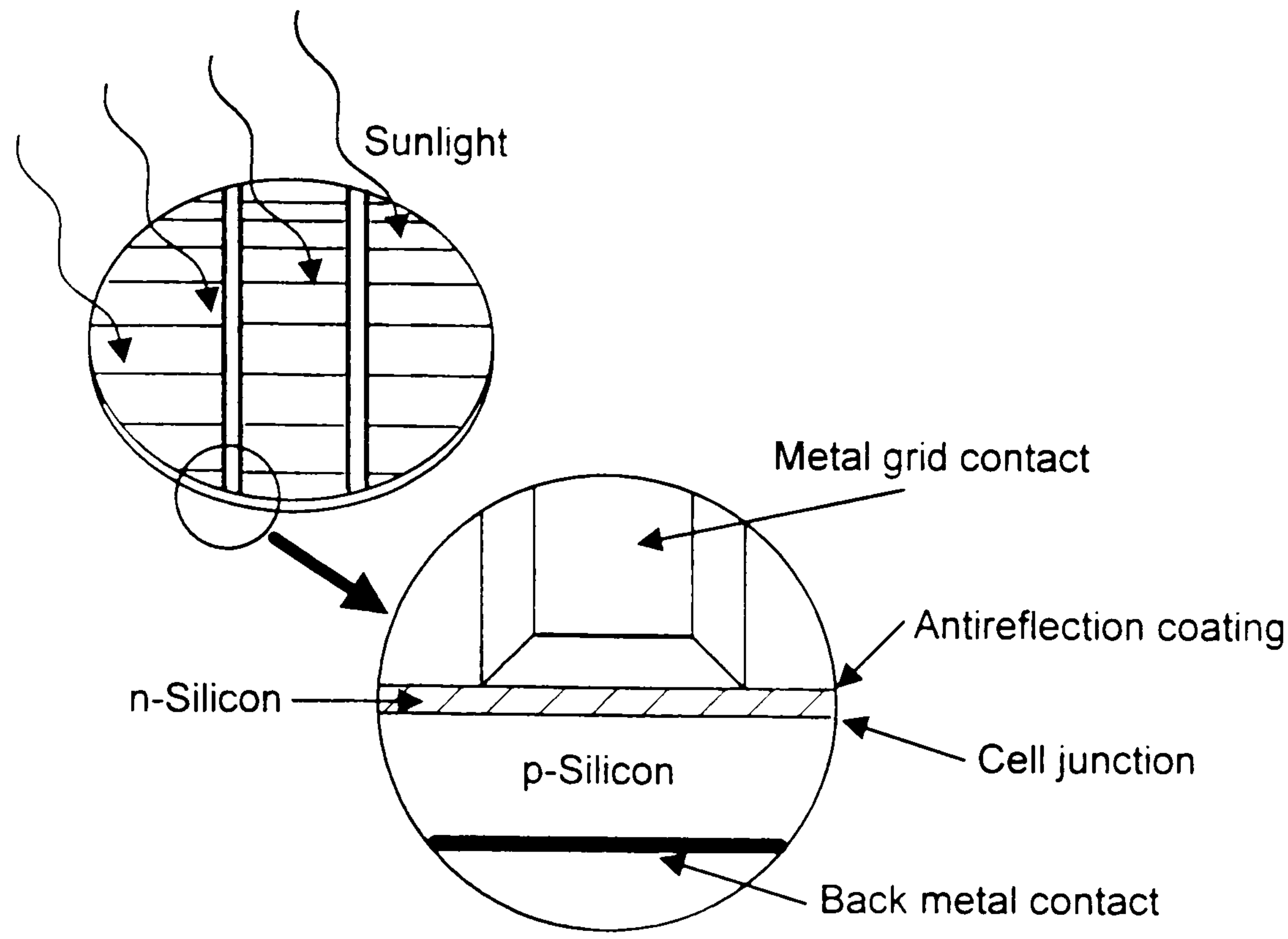

Figure 2.2 A typical single crystal silicon cell consists of a top-surface grid, an antireflection coating, n-silicon, p-silicon and a back metal contact [11,17].

2.3.1 Spectral Response

The energy of the photon (E_P) in electron volts is given by

$$E_p = \frac{h}{\lambda} \tag{2.1}$$

where λ is the wavelength of the photon that is expressed in metres (m), and h is Planck's constant. Thus, infrared photons having a wavelength longer than 1.1 μm cannot release a hole-electron pair. Photons with excess energy each free one electron and the excess energy from each photon is wasted as heat. The spectrum and intensity of sunlight, when the sun is directly overhead, are referred to as "air mass one" (AM1) radiation, for AM0 sunlight occurs in space in the vicinity of the earth.

2.3.2 Equivalent Circuit of a Solar Cell

A solar cell consists of a current source that is shunted by a diode and constant illumination provides constant current generation (I_L). By connecting a load across the terminals of a solar cell, a current I_L can flow through the load and develop a voltage (V) across it. The value of V and I_L, besides depending on the nature of the load, will be related to the photogenerated current I_L and the properties of the diode. These relationships are illustrated in Figure 2.3.

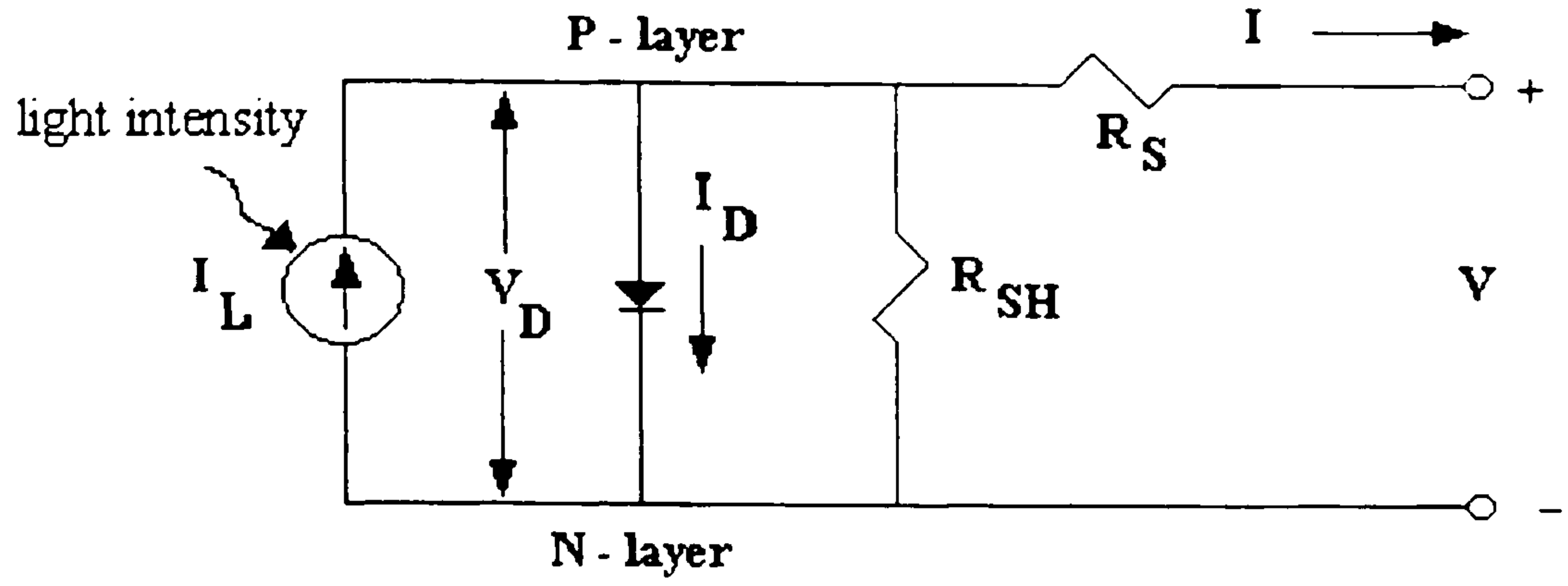

Figure 2.3 Equivalent circuit of a solar cell

Figure 2.3 is the simplified equivalent circuit of a solar cell. It consists of a constant current generator shunted by the junction, which acts like a positive bias diode. The current components are formed by the normal diode dark current (I_D) and the load current. The equation of current-voltage (I-V) characteristic of a solar cell can be written as follows [7,18,19]:

$$I = I_L - I_0\{\exp[\frac{q(V + IR_s)}{AK_BT}] - 1\} - \frac{V + IR_s}{R_{sh}} \tag{2.2}$$

where

I = cell's output current

I_L = light generated current

I_0 = diode saturation current

q = electronic charge (1.6×10^{-19} C)

V = cell's terminal voltage (V)

R_s = series resistance of cell

R_{sh} = shunt resistance of cell

A = an arbitrary curve-fitting constant between 1 and 2

K_B = Boltzman's constant (1.38×10^{-23} $J.K^{-1}$)

T = absolute temperature (K)

Under darkness the solar cell is not active, but it functions as a p-n junction (i.e. as a diode). Externally, it is seen as an energy receiver, it produces neither current nor voltage. The term I_0 { exp $[q(V+IR_s)/(AK_BT)]$ - 1 } defines the diode characteristics of the junction. Thus,

$$I_D = I_0\{\exp[\frac{q(V + IR_s)}{AK_BT}] - 1\} \qquad (2.3)$$

In the case of a solar array consisting of S identical cells or modules in series and P identical cells or modules in parallel, the I-V characteristics of whole generator can be determined by scaling the characteristics of one cell with a factor S in voltage and factor P in current .

2.3.3 Open Circuit Voltage

Under open circuit conditions when I = 0, all generated current must be increasingly conducted through the diode. Open circuit voltage is, thus, determined by the diode characteristic and is given by

$$V_{OC} = \frac{AK_BT}{q}\ln(\frac{I_L + I_0}{I_0}) \qquad (2.4)$$

The open circuit voltage (V_{OC}) increases logarithmically with increasing irradiance level and decreases linearly with an increase in junction temperature [7].

2.3.4 Short Circuit Current

Under short circuit current conditions when V = 0, current through the diode is very small and essentially all generated current is delivered to the output terminals. The series resistance effect is negligible under the short circuit condition. Thus, $I_{SC} = I_L$, the short circuit current of a solar cell can be approximately predicted by

$$I_{SC} = \int_0^\infty R_{(\lambda)}J_{(\lambda)}d\lambda \qquad (2.5)$$

where $R_{(\lambda)}$ is an absolute spectral response of the solar cell and $J_{(\lambda)}$ is the spectral energy of sunlight. However, the value of the short circuit current is proportional to the light intensity (E_i), namely $I_{SC} \propto E_i$ and $I_{SC} = k\,E_i$ (k is a constant).

2.3.5 Maximum Output Power

There is no power generated under short circuit or open circuit. The maximum output power (P_{mp}) produced by the device is reached at a point on the characteristic where the product I-V is maximum. This is shown graphically in Figure 2.4, where the position of maximum power point represents the largest area of rectangle, which can be fixed under the curve.

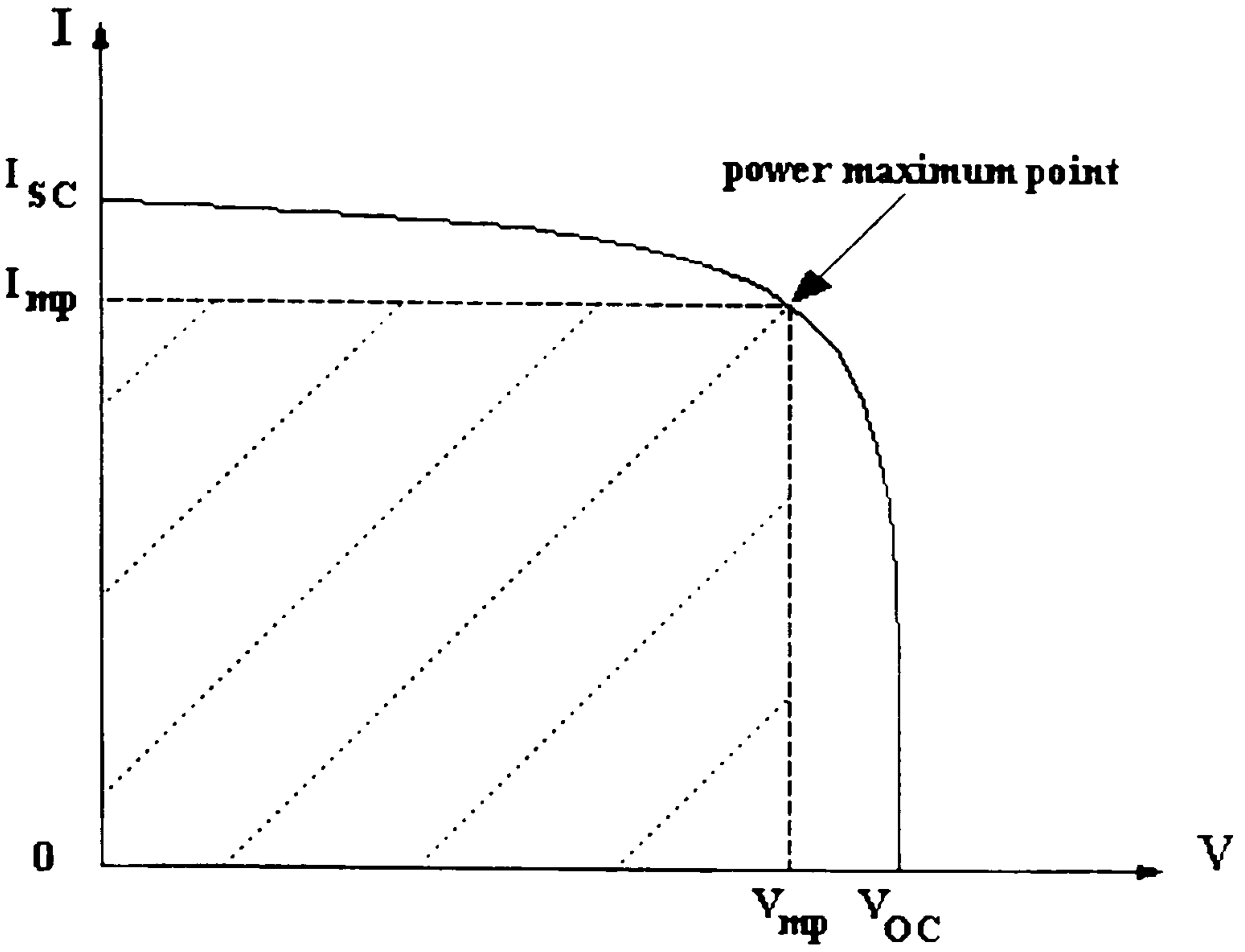

Figure 2.4 A typical I-V characteristic curve of a solar cell.

As can be seen from Figure 2.4, the maximum power (P_{mp}) is I_{mp} multiplied by V_{mp}, where I_{mp} and V_{mp} are the current and voltage at the maximum power point respectively.

2.3.6 Efficiency and Fill Factor

The efficiency of a solar cell is defined as the power P_{mp} produced by the cell at the maximum power point under standard test conditions (irradiance 1000 W/m^2, 25°C, AM 1.5) divided by the power of the radiation incident upon it [18,19].

$$\eta = \frac{I_{mp} \cdot V_{mp}}{P_i \cdot a} \tag{2.6}$$

where

P_i = the incident solar power density

a = the receiving area of the solar cell

The ratio of ($I_{mp}.V_{mp}$) to ($I_{SC}.V_{OC}$) is defined as the fill factor, which enables a further expression for η to be written as:

$$\eta = \frac{FF . I_{SC} . V_{OC}}{P_i . a} \tag{2.7a}$$

$$FF = \frac{\eta \cdot P_i \cdot a}{I_{SC} \cdot V_{OC}} \tag{2.7b}$$

A typical value of η is 12-14% for a single-crystal silicon solar cell and 9-11% for a polycrystalline silicon solar cell. For the fill factor (FF), its value is higher than 0.7 for good solar cells. The fill factor is always less than unity, a typical fill factor of contemporary solar cell range is between 0.75 and 0.80. The fill factor is a practical index for comparing different solar cells under the same conditions, and this is required in manufacturing process control.

2.4 PV Cells and Modules

The conversion of light to electricity is performed by solar cells. These are large area semiconductor diodes, usually silicon wafers 10-15 cm in size, which will normally generate about 35 mA/cm^2 and 550 mV in full sunlight [20]. For most applications, solar cells are mounted in modules, typically with 36 cells in series connection. The cell string is laminated in a transparent soft plastic between a sheet of glass or plastic. This 'laminate' is usually surrounded by an aluminium frame to form the commercial module. Basically, a PV system consists of one or more modules together with the electronic controls, storage units, inverters, mounting structure and wiring, and sometimes the loads. All items other than the PV modules are known collectively as Balance of System (BOS) components. The cost-effectiveness and reliability with which a PV system can provide a service depends as much on the BOS component as on the PV modules themselves, and their future developments are essential factors in the future prospects for PV.

2.4.1 Photovoltaic (solar cell) Materials

At present, the main types of semiconductor materials used are: single-crystal and polycrystalline silicon (Si), amorphous silicon, gallium arsenide (GaAs), cadmium telluride (CdTe) and copper indium diselenide ($CuInSe_2$ or CIS). Single-crystal silicon is presently the most popular option for commercial cells and PV modules. Newcomers, like $CuInSe_2$ and CdTe along with GaAs will play only a minor role in the short term [17,21].

2.4.1.1 Silicon Solar Cells

At present, the cost of solar grade silicon is increasing. This material derives from the waste material from the semiconductor industry and demand is uncomfortably close to the available supply. With present technology, silicon wafer production reaches about 150 MW_P per year. Silicon wafers are slices, about 0.3 mm thick, cut from an ingot of either single crystal or large-grain polycrystalline silicon, for solar cell efficiency, progress has been less visible. Nevertheless, for PV specialists, the pursuit of higher efficiency will continue to be the most fascinating challenge. The best research (highest laboratory) cell is made from Float Zone silicon and has an efficiency of 24% [20]. This is close to the value of 26% that is probably the ultimate achievable efficiency for silicon cells in normal sunlight. Theoretically, solar cells have been predicted that a maximum conversion efficiency of approximately 28% [22] at AM1 intensity (one sun) for a single junction material with a band gap of 1.5 eV. However, manufactured cells still have efficiencies of around 14-17% for single crystal material and 12-14% for polycrystalline wafer. Although performance is enhanced through the more complex designs, these designs raise the potential manufacturing costs. The 100 cm^2 float-zone wafer costs about US$10, but the target cost for commercial production is about US$1[23].

2.4.1.2 Amorphous Silicon

Nowadays, amorphous silicon is commonly used for solar-powered consumer devices that have low power requirements. These cells are made from thin films of amorphous silicon incorporating a few percent of hydrogen. This greatly reduces the electrical resistivity of the material and allows it to be doped n-type or p-type. The design of the cells optimises the collection of current by having a very thin n-layer and p-layer, with an intrinsic layer (i-layer) thick enough to absorb almost all the incident light, to give a p-i-n structure. Amorphous silicon absorbs solar radiation 40 times more efficiently than single-crystal silicon. As a result, a film only about 1 micron thick can absorb 90% of the usable solar energy. This is one of the most important factors affecting its potential for low cost. Other principal economic advantages are that amorphous silicon can be produced at a lower temperature and deposited on low cost substrates. Amorphous silicon has a band-gap energy of about 1.7 eV, which is greater than crystalline silicon's band-gap energy of 1.1 eV. A PV cell's output voltage is directly related to the size of its band-gap, so PV cells made of amorphous silicon have higher output voltages than cells made of crystalline silicon. The higher output voltage compensates for the fact that lower energy photons (with energies below 1.7 eV) are not absorbed by amorphous silicon. The best efficiency recorded for an amorphous silicon cell is 13.6% on a triple junction stack. The U.S. government's aim for development of thin film amorphous silicon cell is over 15% by the year 2005 [23].

2.4.1.3 Copper Indium Diselenide ($CuInSe_2$ or CIS)

CIS is one of the polycrystalline thin film solar cells that comprise many tiny crystalline grains of semiconductor materials. The materials used in polycrystalline thin-film cells have properties that are different from those of silicon. CIS is a semiconductor with a very high optical absorption, so very thin layers will absorb sunlight effectively. It has an extremely high absorption that allows 99% of the available incident light to be absorbed in the first micron of the material, but that is not the only reason that copper indium diselenide is attractive for PV devices. It has also shown very good stability in outdoor testing, an important criterion for commercialization. Adding a small amount of gallium to the absorbing CIS layers boosts the band gap of CIS (from its normal 1 eV), which improves the voltage and therefore the efficiency of the device. The layers of materials in CIS cells can be made by several different processes that were developed in the computer related thin film industry. All of these methods are well established commercially in various industries. The CIS layer itself consists of three different elements, copper, indium, and selenium. One of the most popular preparation methods for the CIS layer is spraying. In this method, a solution of salts of the necessary element is sprayed onto a hot substrate. They react under the elevated temperatures to form the required CIS layer, while the solvent evaporates. CIS layers can also be made by using one of these methods to deposit only the copper and the indium. This is followed by a treatment with hydrogen selenide gas (called selenization) to add the selenium. This approach is considered the most likely to lead to commercial CIS products. Laboratory cells of CIS recently exceeded 19% efficiency [23], while one-square-foot submodules achieved an efficiency above 12%, generating more than 10W of power. A full-sized module has been produced on a pre-commercial scale for many years and has shown excellent stability in outdoor tests.

2.4.1.4 Cadmium Telluride

The other prominent polycrystalline thin film material is Cadmium Telluride (CdTe) with a nearly ideal band gap of 1.44 eV. Cadmium telluride can be deposited as a thin film by a wide variety of methods, which, after appropriate heat treatment, will give material suitable for solar cells. CdTe/CdS cells with efficiencies over 15% [20] have been produced by both vacuum deposition techniques and by electroplating. Modules of these cells have been produced at a research scale and outdoor tests extending for many years have shown little or no degradation. The commercial devices are integrally interconnected modules.

2.4.1.5 Other Promising Types of Cell

There are, at least, two types of solar cell being actively investigated for commercial production, namely the Gratzel cell and the thin film silicon cell.

(i) The Gratzel cell is a photo-electrochemical device, invented by Michael Gratzel. It consists of a layer of titanium dioxide micro-crystals coated with a dye and immersed in a solution. The dye transforms the absorption spectrum of the titanium dioxide from the ultra-violet to the visible/near infrared. There is the promise that the cells could be very cheap to produce. With appropriate choice of dye, the cells can be made transparent to visible light while still having reasonable efficiency to sunlight. They could have a very interesting future as electric generating windows.

(ii) Thin films of polycrystalline silicon can be deposited on low cost substrates by either vapour deposition or deposition from solution. Since the cell is so thin, bulk carrier recombination is greatly reduced, and the thin cells can theoretically be more efficient than a wafer cell. The best efficiencies are about 17% [20] and progress is rapid as the technologies are optimized. The cell on 10×10 cm substrates are available commercially, as a direct replacement for silicon wafers, but the major breakthrough will occur if thin silicon can be deposited on module-sized substrates with integral-interconnection. Such modules could have the price of a thin film module, with the performance of a wafer silicon module.

2.4.2 PV Modules

The interconnection and assembly of PV cells into a safe and stable package are important aspects in the manufacture of terrestrial PV modules. The typical manufacturing process is expected to provide package lifetime in excess of 30 years in the field. In 1997, about 87% of the 125 MW_p of commercial modules used silicon wafer cells. This is about 50% single crystal, 34% polycrystalline and 3% ribbon, in which silicon is grown as a 10 cm wide ribbon, and cut into 10 cm lengths. For most commercial modules the voltage is chosen to be adequate for charging a 12 V battery even in dull conditions, and the module has 36 cells, usually in a 4 by 9 configuration. The module may be designed for 24 V or 48 V output with 72 or 144 cells in series respectively. As the efficiency of cells rises, to perhaps 20% in the next 10-15 years, and production optimisation yields cells with closely similar characteristics, the module efficiency will increase to around 18%.

2.4.2.1 Module of Thin Film Cells

There are three types of thin film cell or module that are likely to be of commercial importance in the next few years. These are amorphous silicon, cadmium telluride/cadmium sulphide and copper indium diselenide/cadmium sulphide cell. All three of the commercial thin film materials are produced as modules with integrally-interconnected cells. This is a technique well suited to large scale, low cost production as the entire module area is coated with the films. Module efficiency, measured in W/unit area of the module, drops as the spaces between cells increase.

1) Modules of Amorphous Silicon

Amorphous silicon is the best developed thin film cell and module [24]. These modules have been commercially available for many years. Its applications are the solar calculator and most consumer products use small modules. The output of single junction cells degrades in outdoor applications over about a year, falling from an initial efficiency by 4-6%. The modules with multijunction cells have an initial efficiency of 8-10%, although the long term performance has yet to be established as they have not been in the field for many years. The degradation is partially annealed out at temperatures of 60°C. There is now an international standard for the accelerated testing of amorphous silicon modules that is providing increased confidence in their performance. However, many modules with efficiencies above 10% have been reported and confirmed. The goal of research in thin film module development is to achieve an efficiency of 15% by 2005 [23,24].

2) Module of CdTe/CdS

Cadmium telluride has an ideal energy gap of 1.45 eV for a solar absorbing material and has been under research since 1970, and is not yet commercially available. However, BP Solar (Europe) and Photon Energy (USA) have both under taken pilot production and are both planning to commence a commercial module product. In addition, BP Solar have recently commissioned a 10 MWh per annum plant in California that is due to ship product by the end of 1998. Another 10 MWh per annum plant was scheduled for completion by ANTEC in Germany in 1999. It is likely that module efficiencies will increase considerably as the uniformity of the materials, and module efficiencies approach those of the small area cells [20].

3) Modules of CIGS/CdS

Copper indium diselenide exhibits the highest optical absorption of all PV materials. CIGS/CdS modules have been in limited pre-commercial production for some years, but it is recently that 10-20 W_P modules have become commercially available, larger modules of 50 W_P should become available later. Modules with an efficiency of 11% have been demonstrated, but the average efficiency of the commercial modules is likely to be around 8%. The optimisation of production processes will bring improved uniformity, and module efficiencies which begin to approach those of small area cells.

2.4.3 Status of PV Module Production

Table 2.1 Status of photovoltaic module production [23]

Photovoltaic module technology	Manufacturers involved	Efficiency (percent)		capacity* (MW)	research, technology and industry needs
		cell	module		
crystalline silicon	BP Solarex Sharp Siemens Solar Astropower Solec	22	10-15	60	• understanding of impurity and defects • understanding of interface and passivation issues for screen printed contacts • Better control of light-texturing, light trapping, and optical modeling • Better impurity separation in silicon feed stock development
Multi crystalline silicon	Photowatt ASE America Evergreen Solar Kyocera BP solarex	18	9-12	70	• Thin layer high quality crystalline silicon formed by low cost production methods • Lower manufacturing cost, complexity • Greater manufacturing capacity
Thin layer silicon	Astropower	17	8	1	(in early development)
Thin film amorphous silicon	Canon Iowa Thin Film BP Solarex USSC Sanyo Energy PV	13	10	19	• Understanding and control of silicon and alloy film structure, with emphasis on deposition rate increasing as structural order increases • Understanding hydrogen's role in: establishing non-structure, alloying and doping, metal stability • Lower capital production cost • Greater manufacturing capacity
Thin film copper indium diselenide	Siemens Solar Global Solar Energy PV Unisolar International Solar Electric	19	12	-	• An integrated, predictive understanding of CIGSS materials and devices • Novel materials, especially with wide energy gaps (>1.7 eV) • Novel deposition techniques of growth mechanisms in existing and novel processes • Development of real time material characterisation for process control • Alternative front and rear contact materials • Scale up and enhance manufacturing base, presently embryonic
Thin film cadmium telluride	BP Solarex First Solar Matsushita	16	9	1	• CdS/CdTe junction modeling and analysis • Understanding basic nature of polycrystalline CdTe needed for truly predictive models, alternative process pathways, and meaningful process monitors and control • Understanding copper's role in back contacts, and exploring copper-free contact • Transparent conducting oxide front layers and their impact on subsequent depositions • Stability-copper diffusion, contact oxidation, contact degradation • Scale up, cell vs. Module performance levels • Better manufacturing base

*Capacity of modules shipped in 1998
CIGS = copper indium gallium diselenide, CdTe = cadmium telluride, CdS = cadmium sulfide

It has been projected that once fully integrated PV production lines reach an annual capacity of over 50 MW_P, a cost objective of less than US$1 per peak Watts installed will be reached. Roof top and other national programmes are stimulating companies to increase their manufacturing capacity rapidly, bringing the 50-100 MW_p factory within reach. However, if the capacity additions are achieved merely by duplicating machines, or by new companies introducing low capacity semi-automation production lines, the cost objectives will not be reached [25]. Significant manufacturing cost reductions can only be achieved either as a sequence of technology breakthroughs or by high-throughput high yield integrated automated production lines using less and lower cost materials. At present, module assembly for relative small volumes of the order of 4,000 modules per shift-year (36 cells per module) is manual. and generally done in countries with a low labour cost [25].

2.5 PV Systems and Components

A PV system is an integrated assembly of modules and other components that is designed to convert solar energy into electricity, and to provide electrical power for a particular service. Basically, there are two different PV systems, namely a grid connected and stand-alone system [26,27]. While in the first case the grid serves as an ideal storage component and ensures system reliability, the stand-alone systems require a storage battery. This battery serves as a buffer between the fluctuating power generated by the PV cells and the load. In order to ensure continuous power supply, even under extreme conditions, a back up generator should be installed.

2.5.1 Advantages of PV Systems

The majority of the population in developing countries live in dispersed communities in rural areas. The provision of an electricity supply to these areas is difficult and costly. Extension of the main grid over difficult terrain is not generally economic for small power loads. PV systems are technically viable and can be economically feasible for many small-scale applications. Some of their principle advantages are as follows [9,28,29]:

- ***PV systems have no fuel requirement*:** In remote areas, kerosene fuel or diesel supplies are erratic and often very expensive. The recurrent costs of operating and maintaining are small, and energy resource from the Sun is free and can be available anywhere.

- ***PV systems are modular design***: A solar array is composed of individual PV modules that can be connected to meet a particular demand and easily replaced.
- ***PV systems are highly reliable***: The reliability of PV modules has been shown to be significantly higher that of diesel generators or wind generators.
- ***PV systems are easy to maintain***: In practice, operation and routine maintenance requirements are simple because there are no moving parts during operation.
- ***PV systems have a long life***: It is expected that the lifetime of PV systems will be 30 years in the future while the current lifetime is about 20 years.
- ***PV systems provide national economic benefits***: Reliance on imported fuels such as coal and oil are reduced.
- ***PV systems are environmentally benign***: There is no harmful pollution for using a PV system and no contribution to "greenhouse gases". A photovoltaic effect converts sun light into electricity completely without noise.
- ***PV systems are economically viable***: Based on a life cycle cost basis and taking into consideration the higher reliability of PV, many small scale applications can be more economically powered by PV than with diesel systems, or other small power supplies.
- ***PV systems have wide power handing capabilities***: The capacity of output power from a PV module can be easily arranged from a few Watt to megawatt depending on the loads. Solar cells can be used in combination with power conditioning circuitry to feed power into a utility grid.
- ***PV systems can be used to improve quality of life***: Night time activities in rural areas that have no electrical power supplies from a utility grid can be done, for example the provision of lighting in a rural school allows evening educational or community activities. Street lighting for public use or refrigeration at a health centre improves effectiveness of immunization programmes.

2.5.2 PV Grid-Connected Systems

In practice, PV systems can be connected to the public grid. This requires an inverter for the transformation of the PV generated DC electricity to the grid AC electricity at the level of grid voltage. Grid-connected PV systems can very greatly in size, but all consist of solar modules, inverters and other components such as wiring and module mounting structures. It is now becoming common for home owners to install a small PV system on their roofs to supply some or all of their electricity needs. For small grid-connected rooftop PV systems, the power produced by the array during the day can be used to supply local loads, with the excess energy fed into the local grid for use by other customers. During the night time, the local loads are simply supplied by the grid. If a PV system is large enough, it can supply more energy into the grid than used by local loads.

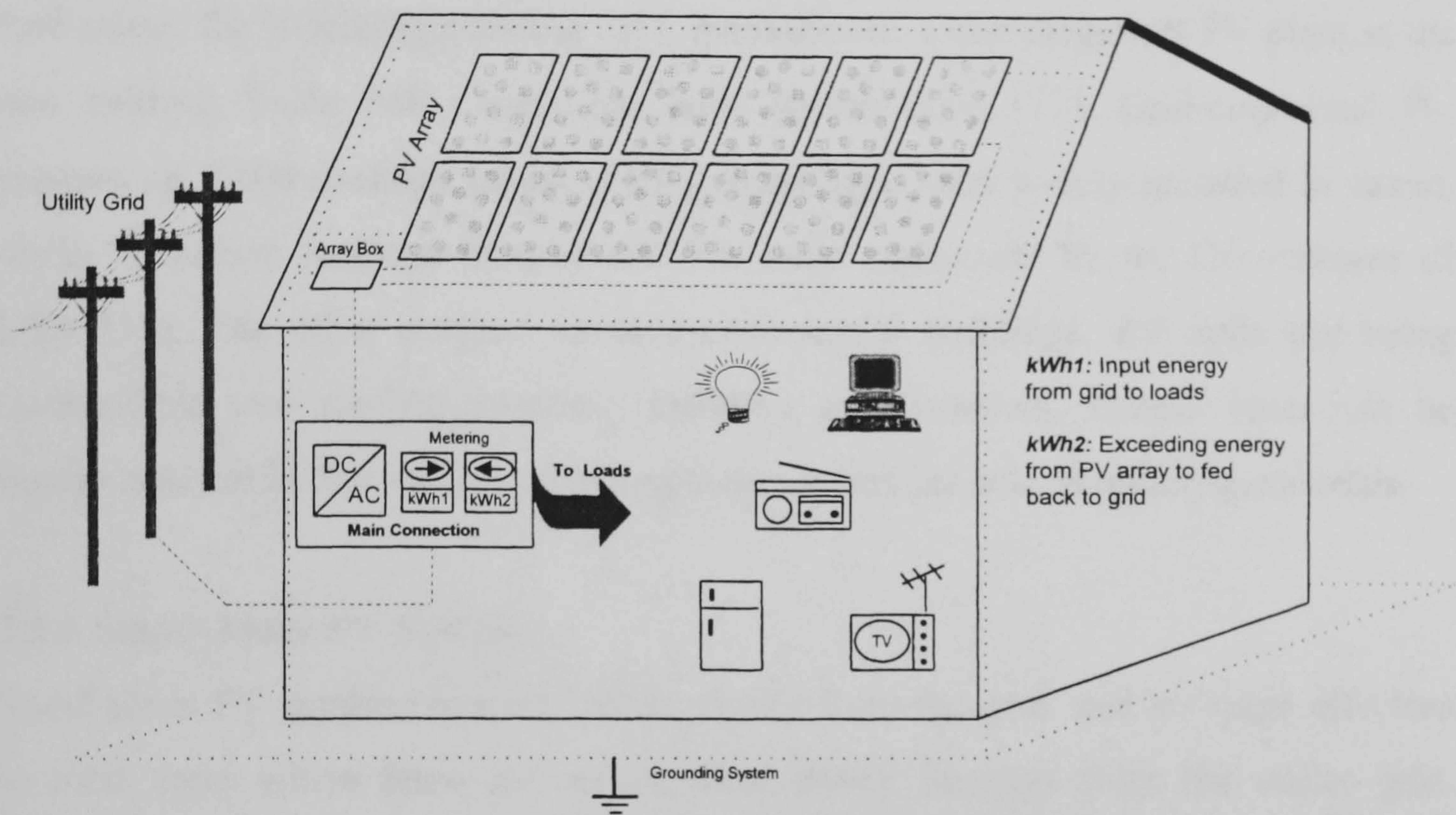

Figure 2.5 Typical feature of a grid-connected system.

One or two energy meters (kWh meters) have to be used at the utility connection. The main attractions of such a system are self sufficiency and the environmental benefits of using renewable energy. The simplicity of the system also means the owners do not need energy storage as batteries because the grid is essentially acting as a storage device. The main technical advance is the availability of low cost high quality inverters. In grid-connected applications, PV systems must compete against the cost of the conventional energy source that is used to supply the grid. PV systems are particularly cost-effective when the utility load and solar resource profiles are well matched. There are many buildings that use both PV systems and normally utility grid to provide electric power in the same building. The Northumberland Building of the University of Northumbria in the UK is one of them. This project was also the first example of integrated PV cladding (39.5 kW_p) in the UK [30]. It is stimulating interest in this technology and providing information for the future integration of PV cladding into appropriate buildings. In Germany, the new and renovated buildings around the Reichstag (Berlin) are connected to a local renewable energy electric grid that includes about 400 kW_p of rooftop and building integrated photovoltaics: this includes 150 kW_p installed on the Chancellery, 100 kW for the Ministry of Economy, 44 kW_p on the Presidential administration building and 36 kW_p on the roof of the Parliament: the Reichstag building [31]. Furthermore, a one megawatt PV plant at the new Munich Trade Fair Centre has been implemented [32]. Grid-connected PV systems on 9,400 rooftops (about 3 kW_p each) have been widely installed in Japan, while "a million rooftops programme" has been announced by the Government of USA [33]. The other projects involve commercial buildings, PV cells are being incorporated into roofing materials, cladding and windows. System costs can be further reduced in this way by offsetting them against the cost of building materials.

2.5.3 Stand-Alone PV Systems

Stand-alone PV systems operate independently from the grid, and are most effective in rural areas where there are no electrical power supplies from the utility grid, especially the locations that have no road access to the villages. The houses in many rural areas are often scattered which means distribution to individual houses will be extremely costly and time consuming to maintain or repair. As a result, a stand-alone PV system is the best choice for installing in these areas. It is categorized in three types, depending on whether they use battery storage and/or auxiliary power source. Figure 2.6 illustrates the types of stand-alone systems.

The first type of stand-alone system is referred to as PV direct type because it powers the load directly without using any battery. Such a system has the most simple configuration for applications that are not critical and match the availability of sunlight, such as calculators, ventilation fans and pumps. Although DC loads are required for this type, AC loads can be connected by using an inverter that is a part of the system, such as a water pumping system in which an AC motor will act as the load. Although PV powers the load directly, some form of power conditioning (i.e., inverter, DC-DC converter, charge controller) may be required to operate the load properly and maximise the PV output.

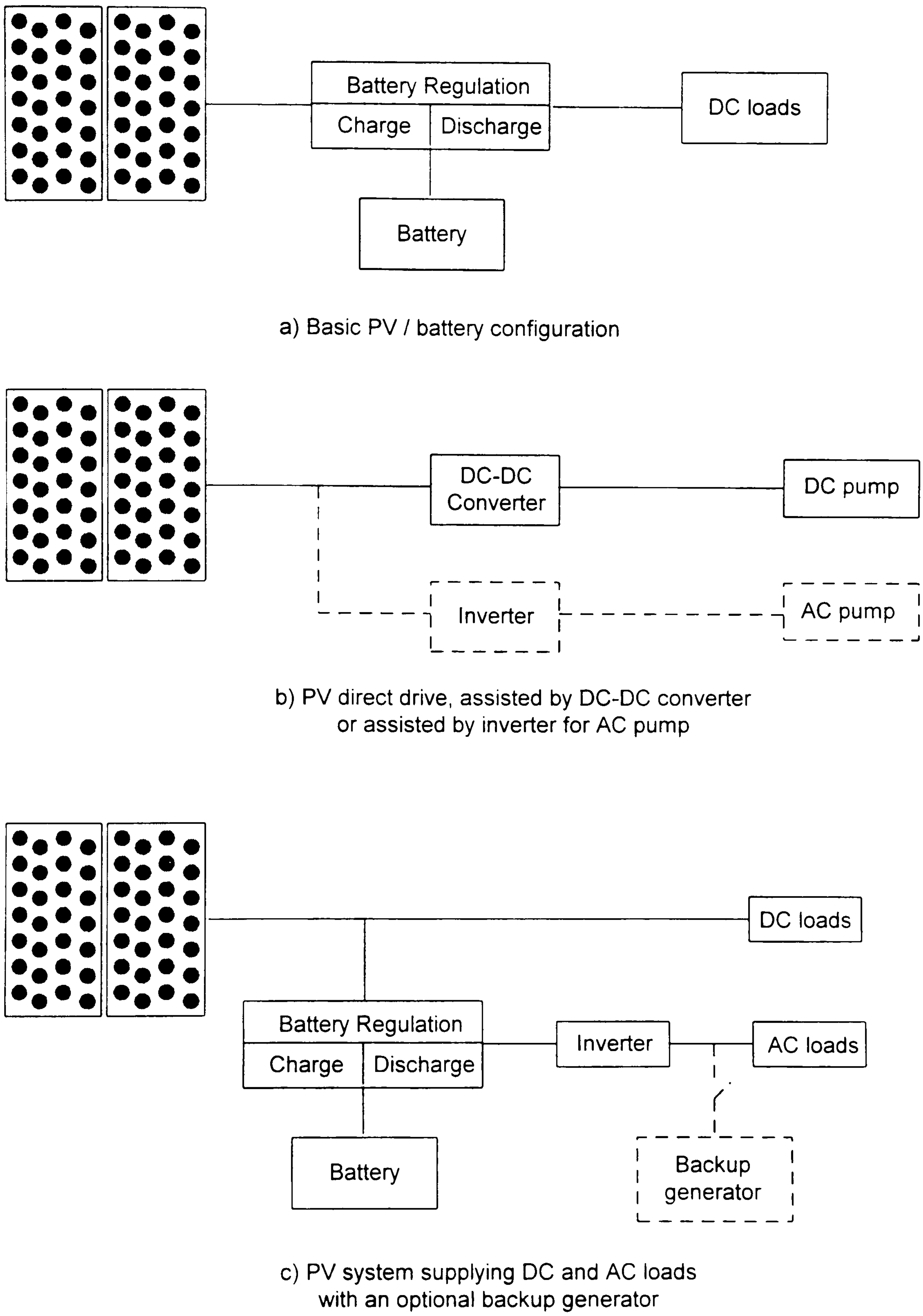

Figure 2.6 Typical types of stand-alone PV power systems.

The next type of stand-alone system is PV with battery. This system includes storage that allows the load to be powered when the PV array cannot supply power directly (for example, at night and during a period of low sunlight). This is the most common type of PV system as it suits a wide range of applications worldwide [34,35]. When the DC loads have to be supplied overnight and during periods of low sunlight, such as telecommunication equipment, cathodic protection, navigation aids, traffic control warning signs, a storage battery with charge controller must be added to the basic DC system. Furthermore, a system with a storage battery is also able to be used with AC loads by adding an inverter.

Another type of PV system, called PV-Hybrid, includes systems that rely on an auxiliary source, generally a fossil or wind generator, to complement the local solar resource,. This type of system is also general use batteries, for short term variations of sunlight condition (on a daily or weekly basis). It is particularly suitable for applications that are critical and need additional backup. A backup generator is commonly used to improve the security of supply, those systems found in regions with large variation in sunlight conditions throughout the year, such as high latitude sites. Generally, all stand-alone PV systems require some form of control or power conditioning. The complexity of the control function depends on system user requirements, the type of system and the number of power sources will be included. At present, sophisticated power conditioners offer options such as periodic equalisation, energy metering, temperature compensation, source management capability, monitoring and remote access by modem.

However, the basic schemes illustrated in Figure 2.6 can be varied to suit particular applications. For example maximum power point tracking (MPPT) may be inserted between the PV array and the rest of the system. The array field may be divided into sub-fields or sub-arrays, each with its own MPPT, to serve different parts of the load. To improve the low-load efficiency of DC to AC conversion, multiple inverters, switched in and out to suit load requirements, may be used instead of a single unit. Backup from the grid or an auxiliary generator may be effected through a battery charger instead of by direct connection to the load.

2.6 Summary

Although PV systems have been widely installed worldwide, PV technologies still need to be continuously developed because they have a goal to reduce the cell cost as much as possible. The growth of the market by a factor of 20-30 will lead to production plant of the scale needed to achieve these costs without the need for any technical breakthroughs. The technologies needed to achieve costs of Euro 0.5/W_P that are coming into commercial production. They also need some product developments, but mainly need market developments to achieve the scale of production required. If thin silicon cells can be deposited on market-sized substrates, then it may be possible to achieve the cost per unit area of thin film modules with the efficiency of wafer silicon modules, and costs below Euro 0.5/W_P [20] will be possible.

This year (2000) at least four fully automated manufacturing lines will be in operation, with overall production capacity in Europe due to reach 100 MW_p [36]. Of this, some 85% will be crystalline silicon cells, 10% cadmium telluride cells and 5% amorphous silicon cells. This is a ten-fold increase in the capacity here only four years ago. The unit size of the largest of these lines is 12.5 MW_P capacity per year. Shell in Gelsenkirchen, Germany set up the first of two such lines for silicon solar cells in one 25 MW_P per year factory in October 1999 [37]. The world market for PV exceeded 200 MW_P in 1999, could rise to 260 MW_P in 2000, 550 MW_P in 2005 and 1800 MW_P in 2010 [38].

Capital is the major cost component of a solar cell PV system. The financial impact of the investment in PV is moderated, or alternatively exacerbated, by the relative efficiency of the appliances or applications that use electrical output from the system. In most cases it is cheaper to invest in improved appliance efficiency than in additional capacity from the solar array. The main point for selection of a PV system is a study of how the energy is to be used and, where appropriate, consideration of alternatives. Simplistically, electricity is best applied to situations where there is no viable alternative, such as for electronic devices (TVs, computers), lighting and electric motor drives in a multitude of applications, of which cathodic protection, telecommunications, water pumping, information services and rural electrification are outstanding.

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Chapter 3

Estimation of Solar Radiation on Inclined Surfaces for Thailand

Chapter 3

3.1 Introduction

Solar radiation incident on PV panels or collector surfaces must be known in order to perform system analysis. Even though the measurement of the total horizontal (global) radiation is available, data of solar radiation on inclined surfaces are practically rare. Most design surfaces of interest are inclined, so it is necessary to estimate the solar radiation on inclined surfaces from data of global radiation. The optimum tilt angle of a PV array is one of the important factors that will be considered for the design of PV systems in order to increase electrical power produced from a PV array. It is usually positioned at an angle to the horizontal surface. As previously researched, the optimum orientation in the northern hemisphere is south facing. The surface azimuth angle is zero degrees measured from south with east positive [1,2,3]. However, the output electrical power from the PV array can be increased if the PV array is suitably adjusted in different seasons and according to climatic data at design location because the sun's path on various days in a year at a particular place is different. In addition, the sun appears to move across the sky from east to west each day and the path of its diurnal motion is longer in summer than in winter. This daily part depends on the time of year and depends on the latitude of site including the sun's declination.

Solar radiation data that are measured on inclined surfaces are not available in many locations in Thailand and have to be estimated from theoretical models. In fact, the monthly average daily global radiation on a horizontal surface for selected provinces of Thailand and the isotropic model are both used to estimate the solar radiation on inclined surfaces. The monthly average daily total radiation on south-facing surfaces of various tilt angles for these provinces has been estimated. The ratios of the average daily beam radiation on the tilted surfaces to that on the horizontal surfaces for the month as a function of the latitudes and monthly average daily conversion factors for global radiation on various provinces have also been computed. The results that are presented in this work can provide a useful database for PV system or solar energy applications in Thailand. The optimum tilt angles in different seasons for Thailand have also been estimated. Furthermore, the solar altitude and the solar azimuth angle between latitude 6° and 20° N in steps of one degree have been determined, because Thailand is situated between these latitude angles. However, the methodical process and the result could be applicable in other places located at the same latitude angle with a similar climate, not just in Thailand.

3.2 Estimation of the Solar Altitude and the Solar Azimuth Angle for Thailand

The geometric relationship between a plane oriented arbitrarily relative to the Earth, such as a solar module, and the incoming beam of solar radiation, is determined by the position of the sun relative to the plane and can be described with several angles. These angles and their interrelationships are depicted as follows:

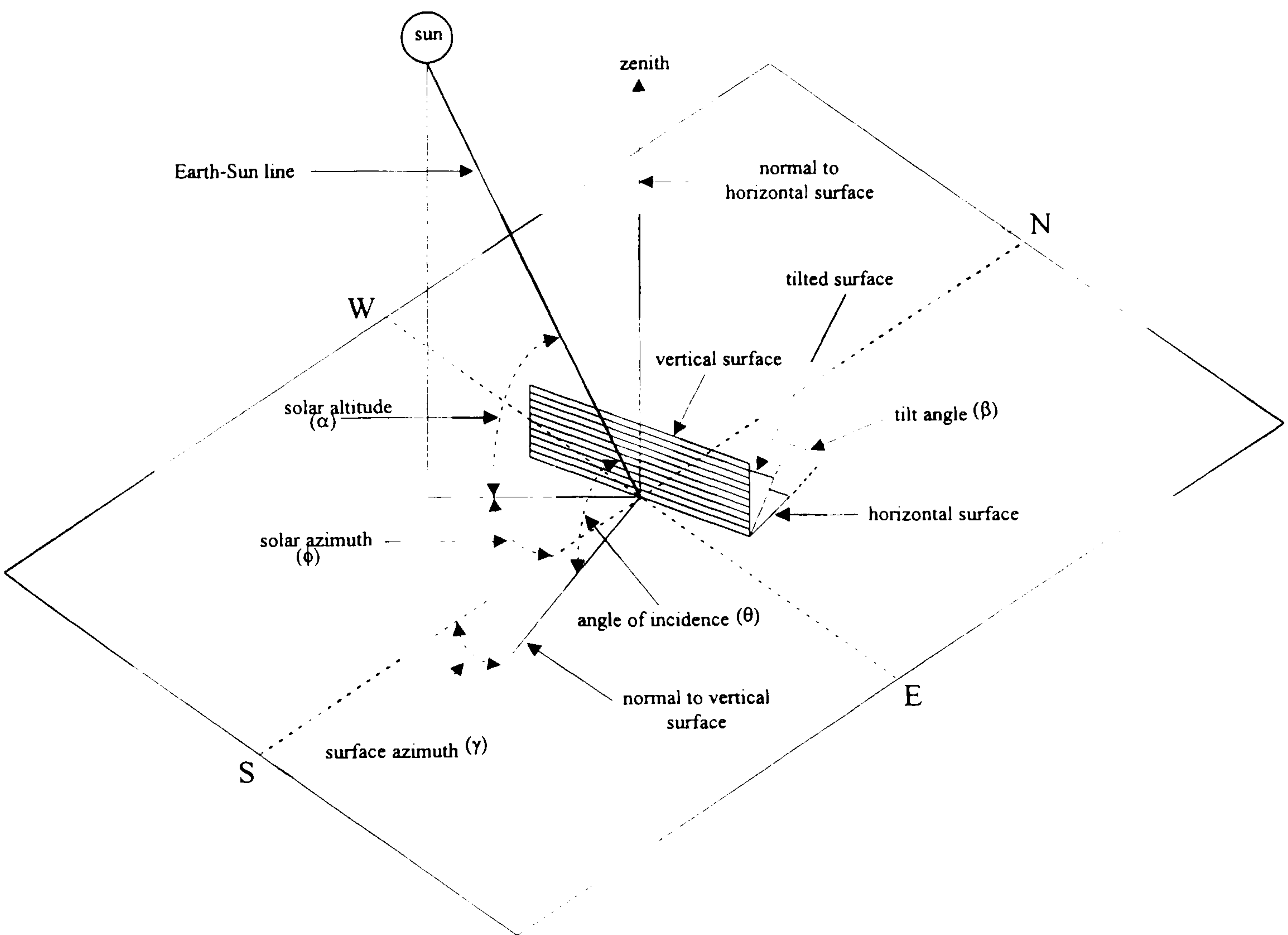

Figure 3.1 Solar altitude, solar azimuth, surface azimuth, slope and angle of incidence on a tilted surface [4].

3.2.1 Solar Angles

To derive the solar altitude, solar azimuth and incident angles from Figure 3.1, the trigonometrical functions can be applied as follows:

3.2.1.1 Solar Altitude Angle (α)

The angle between the horizontal plane and the direct solar beam is the solar altitude angle. It is measured upward from the local horizontal plane to a line between the observer and the sun. The solar altitude angle depends on three fundamental angles, the solar declination (δ), the latitude (L) and the solar hour angle (ω) [4].

$$\sin\alpha = \cos L \cos\delta \cos\omega + \sin L \sin\delta \qquad (3.1)$$

The solar declination angle is a measure of the variation of the sun's position on a seasonal basis. The sun's declination from the equator can be approximately determined by the following equation [5]:

$$\delta = (23.45).\sin\left[360\frac{(284 + n)}{365}\right] \qquad (3.2)$$

where n is the number of days of the year, ranging from 1 on 1st January to 365 on 31st December. The hour angle is the product of the sun's apparent angular rate of moment, 1° per 4 minutes (or 15° per hour) and solar noon being zero, and each hour is 15° of longitude with morning positive and after noon negative [6].

$$\omega = 15(12 - t) \qquad (3.3)$$

where t is a time expressed in hours and ω is expressed in degrees.

3.2.1.2 Solar Azimuth Angle (ϕ)

The angle between the south-north line at a given location and the projection of the earth-sun line in the horizontal plane is called the solar azimuth. It can be written as:

$$\sin\phi = \frac{(\cos\delta \sin\omega)}{\cos\alpha} \qquad (3.4)$$

The azimuth angle will be greater than 90° for some hours of the day when the length of day is greater than 12 hours, since the equation 3.4 must also be evaluated relative to the time of year for which a calculation is being made. To compute the solar altitude (sun elevation) angle, it is sufficient to apply the inverse sine function in equation 3.4. The solar azimuth has also been calculated. The results of solar altitude angle and solar azimuth angle for each hour between 6° and 20° northern latitude of the equator can be seen in appendix A. They are suitable for use in Thailand and are applicable in other places with the same latitude angle and a similar climate.

3.2.1.3 Surface Azimuth Angle (γ)

The angle between the normal to the surface and true south. It is the deviation of the normal to the surface from the local meridian, the zero point being due south, east positive and west negative.

3.2.1.4 Tilt Angle (β)

The angle between the horizontal plane and the surface in question (see Figure 3.1).

3.2.1.5 Incident Angle (θ)

The angle is between the direct solar beam and a line normal to the irradiated surface, the angle being measured between the beam and the normal to the plane. The incident angle, θ, can be calculated from the following equation [6]:

$$\begin{aligned}\cos\theta = {} & \sin\delta\sin L\cos\beta - \sin\delta\cos L\sin\beta\cos\gamma \\ & + \cos\delta\cos L\cos\beta\cos\omega \\ & + \cos\delta\sin L\sin\beta\cos\gamma\cos\omega \\ & + \cos\delta\sin\beta\sin\gamma\sin\omega\end{aligned} \qquad (3.5)$$

As an example, calculate the angle of incidence of beam radiation on a surface located at Udon Thani of Thailand (17.38° N), at 14.30 hours on February 15, if the surface is tilted 20° from the horizontal and is pointed 15° west of south. Under these conditions, the declination angle (δ) is -13.29°, the hour angle (ω) is -37.5°, and the surface azimuth angle (γ) is -15°. Using the slope of 20°, then the angle of incidence is 34°. An additional angle may also be defined. The most frequently used is the Zenith angle (θ_Z), the angle between the beam from the sun and the vertical. Hence, the solar altitude angle (α) is equal to (90°-θ_Z). In many cases, the equation relating these angles is simplified, for example in the case where the PV arrays are fixed, facing toward the equator, γ = 0° and last term is dropped out. For vertical surfaces where β = 90°, the first and third terms are dropped out. For a horizontal surface where β = 0°, only the first and third terms remain, and the angle of incidence (i.e., the zenith angle of the sun) is

$$\cos\theta_Z = \sin\delta\sin L + \cos\delta\cos L\cos\omega \qquad (3.6)$$

As an example, for Udon Thani of Thailand at 14.30 hours on February 15. the zenith angle of the sun is 48°. Useful relationships for the angle of incidence on surfaces sloped to the north or south can be derived from the fact that a surface with slope β to the north or south (i.e.,γ=0°) has the same angular relationship to beam radiation as a horizontal surface at an artificial latitude of (L - β).

$$\cos\theta_T = \sin\delta\sin(L-\beta) + \cos\delta\cos(L-\beta)\cos\omega \qquad (3.7)$$

Note that the slope β is measured from the horizontal to the plane of the surface in question and it is positive when the slope is toward the equator.

3.2.2 Solar Time

Solar time intervals can also be derived from the incidence angle equation. These times are geometric times measured from the centre of the solar disk and not conventional times measured from the apparent upper edge. From the equation 3.6 this can be solved for the sunset hour angle, ω_S , when $\theta_Z = 90°$.

$$\cos\omega_S = -\frac{\sin L \sin\delta}{\cos L \cos\delta} = -\tan L \tan\delta \qquad (3.8)$$

Now day length or possible sunshine hours, N, is given by

$$N = \frac{2\omega_S}{15} = \frac{2}{15}\cos^{-1}(-\tan L \tan\delta) \qquad (3.9)$$

3.3 Estimation of the Components of Solar Radiation

3.3.1. Extraterrestrial Radiation on a Horizontal Surface.

The expressions can be obtained for different time periods (an hour, a day, etc.) from geometrical considerations. The radiation over a period of 1 hour, I_0 , is given by:

$$I_0 = E_{sc}\varepsilon_0\cos\theta_Z \qquad (3.10)$$

where I_0 is a power density and θ_Z is the zenith angle corresponding to the point in time half way through the hour in question [6]. E_{sc} is the solar constant that is defined as the total solar energy irradiance (or power flux per unit of area) incident on a surface exposed normally to rays of the Sun at one astronomical unit and its value is 1376 W/m^2 [6,7]. The ε_0 is the eccentricity correction factor of the earth's orbit and the value of ε_0 can be calculated from the following equation [6]:

$$\varepsilon_0 = 1 + 0.033\cos\left(\frac{360 \times n}{365}\right) \qquad (3.11)$$

The irradiation over a period of 1 day is given by

$$H_0 = \frac{24}{\pi} E_{sc}\varepsilon_0 \cos\phi \cos\delta\left(\sin\omega_S - \omega_S \cos\omega_S\right) \qquad (3.12)$$

where ω_S is the sunset hour angle expressed in radians.

3.3.2 Beam and Diffuse Components of Daily Radiation.

Measured global solar radiation on a horizontal surface consists of the direct and diffuse components of solar radiation. Studies of available daily radiation data have shown that the average fraction which is diffuse, H_d/H, is a function of K_T, the day's clearness index where H_d and H are daily total diffuse radiation and daily total radiation respectively incident on a horizontal surface expressed in kWh/m^2. K_T is the ratio of daily total radiation on a horizontal surface to that of daily extraterrestrial radiation on a horizontal surface (H/H_0). The correlation by Erbs et. al has been used to calculate H_d as shown in Figure 3.2 [8].

3.3.3 Beam and Diffuse Components of Monthly Radiation

In this case, the monthly fraction that is diffuse, $\overline{H}_d/\overline{H}$, is a function of monthly average clearness index ($\overline{K}_T$). Where $\overline{H}_d$ and $\overline{H}$ are monthly average daily diffuse radiation and monthly average daily total radiation respectively that are incident on a horizontal surface expressed in kWh/m^2. $\overline{K}_T$ is the ratio of monthly average daily total radiation on a horizontal surface to that monthly average daily extraterrestrial radiation on a horizontal surface $\overline{K}_T = \overline{H}/\overline{H}_0$. Erbs et al [8] developed a monthly average diffuse fraction correlation from the daily diffuse correlations. There is a seasonal dependence in that the winter curve lies below the other. This is indicating lower moisture and dust in the winter sky with resulting lower fractions of diffuse radiation. The equations for the correlation are as follows:

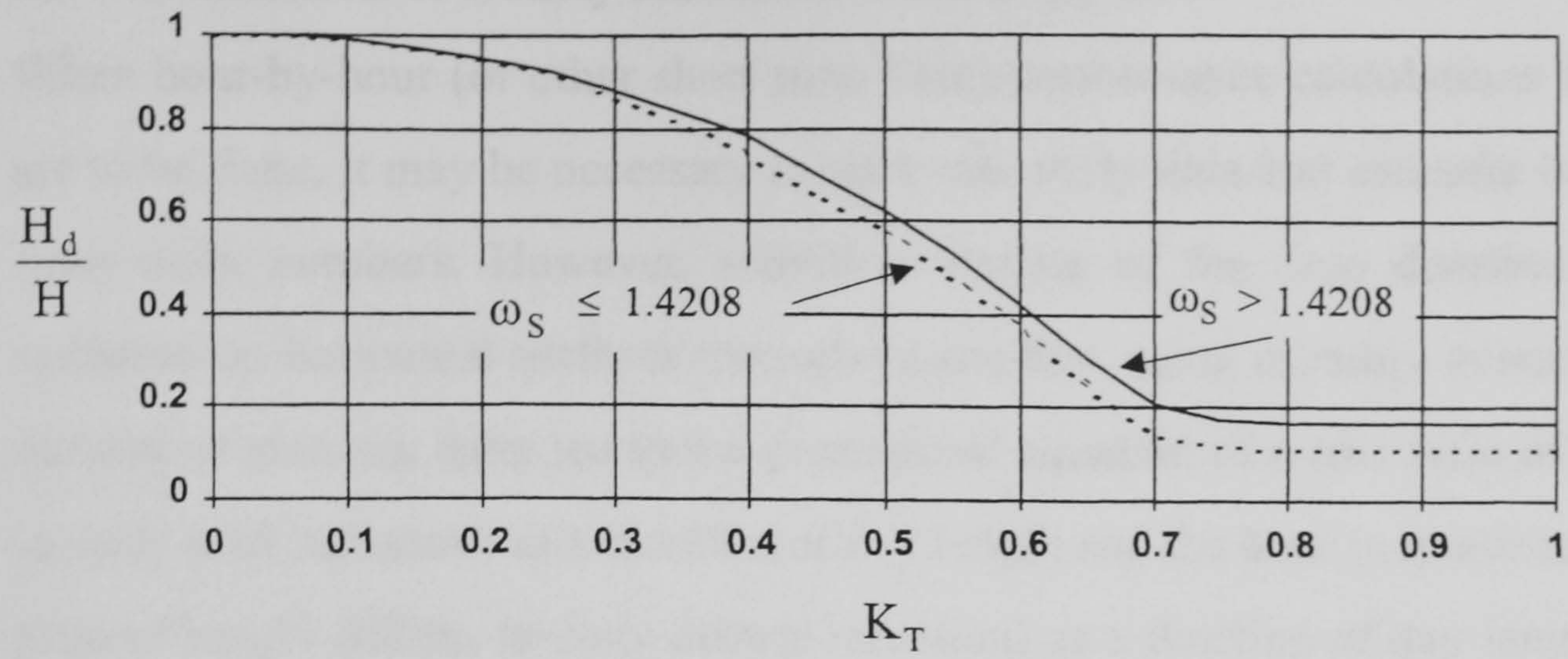

Figure 3.2 Suggested correlation of daily diffuse fraction with K_T [8]

For $\omega_S \leq 1.4208$

$$\frac{H_d}{H} = \begin{cases} 1.0 - 0.2727K_T + 2.4495K_T^2 - 11.9514K_T^3 + 9.3879K_T^4 & \text{for } K_T < 0.715 \\ 0.143 & \text{for } K_T \geq 0.715 \end{cases} \tag{3.13a}$$

For $\omega_S > 1.4208$

$$\frac{H_d}{H} = \begin{cases} 1.0 + 0.2832K_T - 2.557K_T^2 + 0.448K_T^3 & \text{for } K_T < 0.722 \\ 0.175 & \text{for } K_T \geq 0.722 \end{cases} \tag{3.13b}$$

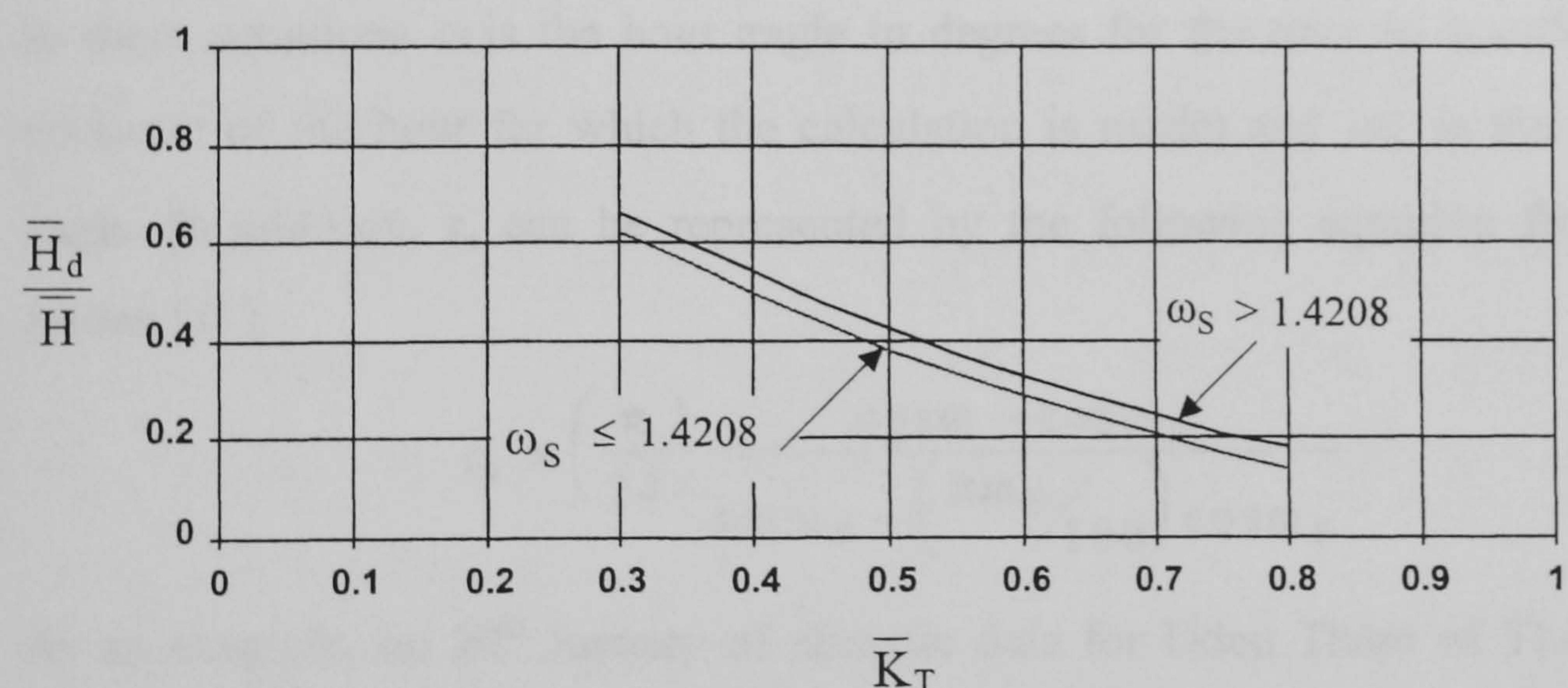

Figure 3.3 Suggestion correlation of monthly diffuse fraction with $\overline{K}_T$ [8]

For $\omega_S \leq 1.4208$ and $0.3 \leq \overline{K}_T \leq 0.8$

$$\frac{\overline{H}_d}{\overline{H}} = 1.391 - 3.560\overline{K}_T + 4.189\overline{K}_T^2 - 2.137\overline{K}_T^3 \tag{3.14a}$$

and for $\omega_S > 1.4208$ and $0.3 \leq \overline{K}_T \leq 0.8$

$$\frac{\overline{H}_d}{\overline{H}} = 1.311 - 3.022\overline{K}_T + 3.427\overline{K}_T^2 - 1.821\overline{K}_T^3 \tag{3.14b}$$

3.3.4 Estimation of Hourly Radiation from Daily Data

When hour-by-hour (or other short time base) performance calculations for a system are to be done, it may be necessary to start with daily data and estimate hourly values from daily numbers. However, statistical studies of the time distribution of total radiation on horizontal surfaces throughout the day, using monthly average data for a number of stations, have led to the generalised equation of r_t (the ratio of hourly total to daily total radiation) as a function of day length and the hour in question, and r_d (the ratio of hourly diffuse to daily diffuse radiation) as a function of day length and time. The hours are designated by the time for the midpoint of the hour, and the days are assumed to be symmetrical about solar noon. The values of r_t and r_d are represented by the following equation from Collares-Pereira and Ralb [9-10].

$$r_t = \frac{\pi}{24}(a + b.\cos\omega)\frac{\cos\omega - \cos\omega_S}{\sin\omega_S - \left(\pi\omega_S / 180\right)\cos\omega_S} \qquad (3.15)$$

The coefficients a and b are given by:

$$a = 0.4090 + 0.5016\sin(\omega_S - 60)$$

$$b = 0.6609 - 0.4767\sin(\omega_S - 60)$$

In these equations ω is the hour angle in degrees for the time in question (i.e., the midpoint of the hour for which the calculation is made) and ω_S is the sunset hour angle. In addition, r_d can be represented by the following equation from Liu and Jordan [11]:

$$r_d = \left(\frac{\pi}{24}\right)\frac{\cos\omega - \cos\omega_S}{\sin\omega_S - \left(\pi\omega_S / 180\right)\cos\omega_S} \qquad (3.16)$$

As an example, on 20th January of climatic data for Udon Thani of Thailand, daily solar radiation on a horizontal surface on that day is 4.804 kWh/m^2. To estimate the average diffuse, the average beam and the average total radiation for the 10 to 11 hours can be calculated as follows.

The mean daily extraterrestrial radiation (H_o) for January at Udon Thani is 7.834 kWh/m^2 (where L = 17.38°, δ = -20.34°, ω_S = 83.33°). From the equations above of r_t and r_d, the daily diffuse radiation can be found to be 1.537 kWh/m^2 and r_d = 0.128, r_t

= 0.135, (where the day length is equal to 11.11 hours). The average diffuse radiation and the average total radiation between 10.00-11.00 hours are 0.1967 and 0.6485 kWh/m^2 respectively, and the average beam radiation is 0.4518 kWh/m^2.

3.3.5 Radiation on Sloped Surfaces

Generally, solar radiation that is measured on a horizontal surface is available, but solar radiation on inclined surfaces is a very important data to use in solar applications. In practice, measurements of these data are rare and have to be estimated from theoretical models. Different mathematical models have been developed by Liu and Jordan [11], Hay and David [12] and Klucher [13]. However, an isotropic model by Liu and Jordan has been widely used. To obtain the direct and diffuse (sky) radiation received by a tilted surface, the corresponding radiation on a horizontal surface should be multiplied respectively by the appropriate conversion factors. The conversion factor for beam radiation is $\cos\theta_t/\cos\theta_h$, for a surface tilted β degrees from the horizontal surface toward the equator.

$$\cos\theta_t = \cos(L-\beta)\cos\delta\cos\omega + \sin(L-\beta)\sin\delta \tag{3.17}$$

where

$$R_b = \frac{\cos\theta_t}{\cos\theta_h} = \frac{\cos(L-\beta)\cos\delta\cos\omega + \sin(L-\beta)\sin\delta}{\cos L\cos\delta\cos\omega + \sin L\sin\delta} \tag{3.18}$$

where R_b is a conversion factor for daily beam radiation, it has no dimension. The conversion factor of diffuse radiation (R_d) is $(1+\cos\beta)/2$, if the diffuse radiation is isotropic. That is the ratio of diffuse on the tilted surface to that on the horizontal surface. The surface has a view factor to the ground of $(1-\cos\beta)/2$, and, if the surroundings have a diffuse reflectance of ρ_g for the total solar radiation, a conversion factor for reflected radiation (R_g) is $\rho_g.(1-\cos\beta)/2$ where ρ_g is the ground reflectance of solar radiation (values of ρ_g are given in Table 3.1). The total solar radiation on the tilted surface for an hour is the sum of three terms as follows:

$$I_T = I_b R_b + I_d\left(\frac{1+\cos\beta}{2}\right) + I_{th}.\rho_g.\left(\frac{1-\cos\beta}{2}\right) \tag{3.19}$$

where

I_T = total hourly radiation on the tilted surface

I_{th} = total hourly radiation on a horizontal surface

I_b = hourly beam radiation on a horizontal surface

I_d = hourly diffuse radiation on a horizontal surface

This procedure is repeated for each hour of the day. The summary of each hour in a days duration of sunshine is the daily total radiation on a tilted surface.

3.4 Solar Radiation on Inclined Surfaces Using a Computer Programme

Measured solar radiation on inclined (tilted) surfaces are not available in many places of Thailand and have to be estimated from a theoretical model. To compute the total solar radiation on the tilted surfaces from measurements on a horizontal surface is complicated. Basically, the monthly average daily total radiation on the tilted surfaces can be estimated by individually considering the direct beam, diffuse and reflected component of the radiation that is incident on the tilted surfaces.

Table 3.1 Solar reflectivity values for 15 characteristic surfaces [5,14].

Surface	Average Reflectivity
Snow (freshly fallen or with ice film)	0.75
Water surfaces (relatively large incidence angles)	0.07
Soils (clay, loam, etc.)	0.14
Earth roads	0.04
Coniferous forest (winter)	0.07
Forest in autumn, ripe field crops, plants	0.26
Weathered blacktop	0.10
Weathered concrete	0.22
Dead leaves	0.30
Dry grass	0.20
Green grass	0.26
Bituminous and gravel roof	0.13
Crushed rock surface	0.20
Building surfaces, dark (red brick, dark paints, etc.)	0.27
Building surfaces, light (light brick, light paints, etc.)	0.60

The solar radiation climate of Thailand can be generally stated that [14,15] during the spring, the weather is fine and the whole of Thailand has from 8 to 9 hours of sunshine per day. This is the season of maximum radiation. In summer, the duration of sunshine is between 5 and 7 hours per day. During the autumn, the duration of sunshine is about 5 to 6 hours per day in many areas. There is heavy rain and the lowest radiation of the year is experienced. In winter, the weather is quite fine and there is about 8 to 9 hours of sunshine per day over the most of the country. The seasonal periods of Thailand can be divided into 4 seasons as follows:

Table 3.2 The seasonal periods of Thailand

Month	Season
February - April	Spring
May - July	Summer
August - October	Autumn
November - January	Winter

Tables in reference 15 provide the global solar radiation for selected provinces of Thailand estimated from mean daily duration of sunshine in each 1½ month period at the 18 stations and sunshine averages over 15 to 20 years. The monthly average daily global radiation on the horizontal surfaces for selected provinces of Thailand has been used in the present study to estimate the solar radiation on the tilted surfaces. Table 3.3 shows the values of the solar radiation expressed in kWh/m^2.

Table 3.3 Monthly average daily global radiation for selected provinces of Thailand [kWh/m^2]

Province	Month											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Chiang Rai	4.237	4.608	4.997	5.275	5.389	4.717	4.591	4.473	4.636	4.456	4.270	3.765
Chiang Mai	4.469	4.698	5.345	5.491	5.511	4.787	4.571	4.369	4.671	4.694	4.704	4.322
Loei	4.201	4.479	4.857	5.031	5.097	4.636	4.528	4.427	4.125	4.118	4.109	3.997
Nakhon Phanom	4.268	4.284	4.601	4.810	4.887	4.299	4.239	4.183	4.345	4.471	4.578	4.253
Sakon Nakhon	4.523	4.521	4.985	5.075	5.076	4.520	4.477	4.438	4.706	4.711	4.711	4.555
Phitsanulok	4.527	4.625	5.240	5.463	5.540	4.868	4.694	4.532	4.357	4.519	4.665	4.485
Khon Kaen	4.625	4.674	5.008	5.231	5.329	4.857	4.707	4.567	4.427	4.649	4.847	4.578
Roi Et	4.369	4.423	5.124	5.263	5.324	5.031	4.881	4.741	4.520	4.603	4.671	4.369
Nakhon Sawan	4.560	4.661	5.136	5.233	5.238	4.682	4.532	4.392	4.287	4.473	4.643	4.508
Ubon Ratchthani	4.624	4.732	5.229	5.208	5.167	4.915	4.735	4.567	4.404	4.571	4.723	4.567
Korat	4.555	4.644	5.054	5.124	5.144	4.892	4.778	4.671	4.404	4.536	4.655	4.508
Surin	4.648	4.746	5.275	5.171	5.074	4.822	4.774	4.729	4.613	4.684	4.747	4.601
Bangkok	4.641	4.713	5.403	5.124	4.906	4.613	4.451	4.299	4.136	4.346	4.545	4.625
Chanthaburi	4.742	4.743	5.089	4.803	4.571	4.183	4.045	3.916	3.811	4.218	4.606	4.764
Phuket	4.844	5.140	5.507	4.907	4.496	4.392	4.362	4.334	4.113	4.268	4.422	4.624
Songkhla	4.496	4.990	5.368	5.054	4.824	4.636	4.678	4.717	4.415	4.235	4.068	4.113

3.4.1 A Model of Estimation

Total solar radiation arriving on an inclined surface has three components, namely beam radiation, sky-diffuse radiation and ground-reflected radiation. Calculation of the monthly average daily total radiation on the tilted surface is needed for use in solar energy design procedures. The method of Liu and Jordan has been widely used and makes calculation of radiation on tilted surface easy [6,11,16], if the diffuse and ground reflected radiation is each assumed to be isotropic. The results of estimation from this research work are based on the isotropic model. Thus, for a surface that is tilted at an angle from the horizontal surface, the monthly average daily total radiation is given by

$$\overline{H}_T = \overline{H}_B + \overline{H}_D + \overline{H}_G \tag{3.20}$$

where $\overline{H}_T$ is monthly average daily total radiation on a tilted surface, $\overline{H}_B$ is beam or direct radiation, $\overline{H}_D$ and $\overline{H}_G$ are diffuse radiation and ground-reflected radiation on a tilted surface respectively. The beam radiation received on an inclined surface can be expressed as

$$\overline{H}_B = \left(\overline{H} - \overline{H}_d\right)\overline{R}_b \tag{3.21}$$

where $\overline{H}$ and $\overline{H}_d$ are the monthly average daily total radiation and diffuse radiation on a horizontal surface respectively. $\overline{R}_b$ is the ratio of the average daily beam radiation on a tilted surface to that on a horizontal surface for the month. Liu and Jordan suggest that it can be estimated by assuming that it has the value that would be obtained if there were no atmosphere. For surfaces that are sloped towards the equator in the northern hemisphere, such as in Thailand, the surface azimuth angle (γ) is taken to be zero. The value of $\overline{R}_b$ can be expressed as [11,16]:

$$\overline{R}_b = \frac{\cos(L-\beta)\cos\delta\sin\omega'_S + \left(\pi/180\right)\omega'_S\sin(L-\beta)\sin\delta}{\cos L\cos\delta\sin\omega_S + \left(\pi/180\right)\omega_S\sin L\sin\delta} \tag{3.22a}$$

where ω'_S is the sunset hour angle for the tilted surface for mean day of the month. It is also given by

$$\omega'_S = \min\begin{bmatrix}\cos^{-1}(-\tan L\tan\delta) \\ \cos^{-1}\left(-\tan(L-\beta)\tan\delta\right)\end{bmatrix} \tag{3.22b}$$

where "min" means the smaller of the two terms in the brackets. L and β are the angles of latitude and surface slope from the horizontal and both are expressed in degrees. δ is solar declination that is also expressed in degrees. ω_S is the sunset hour angle expressed in degrees, and is equal to $\cos^{-1}(-\tan L \tan\delta)$. It is assumed as an approximation that the diffuse-sky radiation is isotropic, i.e., it is uniform in all directions. The equations of conversion factor for diffuse-sky radiation (R_d) and conversion factor for the ground-reflected radiation (R_g) can be expressed as follows: (i) $R_d = (1+\cos\beta)/2$ and (ii) $R_g = \rho_g.(1-\cos\beta)/2$. Thus, R_d is the ratio of diffuse on a tilted surface to that on a horizontal surface and ρ_g is ground reflectance (albedo). Based on the isotropic model, the monthly average daily total radiation on the tilted surface can be expressed as [6,16]:

$$\overline{H}_T = \left(\overline{H} - \overline{H}_d\right)\overline{R}_b + \overline{H}_d\left(\frac{1+\cos\beta}{2}\right) + \overline{H}.\rho_g\left(\frac{1-\cos\beta}{2}\right) \tag{3.23}$$

When $\overline{H}_T$ has been determined, the ratio of total radiation on the tilted surface to that on the horizontal surface is given by $\overline{R} = \overline{H}_T/\overline{H}$. In addition, the value of $\overline{H}_d$ can be determined from the ratio of $\overline{H}_d/\overline{H}$ that Erbs at el. [see previous topic] derived for a seasonal monthly average daily diffuse correlation, where $\overline{K}_T$ (monthly average daily clearness index) is the ratio of $\overline{H}/\overline{H}_0$. $\overline{H}_0$ is the extraterrestrial radiation on a horizontal surface on mean day (n) of the year, as suggested by Klein [17] and it is shown in Table 3.4. The value of the solar constant used in this work is 1367 W/m^2 for calculation of the value of $\overline{H}_0$ on mean day of the year.

Table 3.4 Recommended average day for each month [17]

Month	Day of the year	Date
January	17	17 Jan.
February	47	16 Feb
March	75	16 Mar.
April	105	15 Apr.
May	135	15 May
June	162	11 Jun.
July	198	17 Jul.
August	228	16 Aug.
September	258	15 Sep.
October	288	15 Oct.
November	318	14 Nov.
December	344	10 Dec.

3.4.2 A Computer Programme Developed for Estimation of Solar Radiation on Inclined Surfaces for Thailand

As can be seen from the previous topic, there are many complex equations and many conditions that are concerned with the calculation of solar radiation, especially on inclined surfaces. Methodical analysis in this topic needs to be done by a computer programme to ensure that the results are accurately calculated. Since manual calculation for prediction of solar radiation is a laborious job, and may cause errors in handling numerous amount of data, a computer programme has been specifically developed with C-language in this research work to provide a convenient tool and flexibility for users.

A computer programme that was specifically developed can be modified to estimate 4 objectives as follows:

- To estimate the daily total solar irradiation on an inclined surface from measurable data of the daily total solar irradiation on a horizontal surface in one year and optimum tilt angle in different seasons for Thailand.
- To estimate the monthly average daily total radiation on the south-facing surfaces on various tilted angles for selected provinces of Thailand.
- To estimate the ratios, ($\overline{R}_b$), of the average daily beam radiation on the tilted surfaces to that on the horizontal surfaces for the month as a function of the latitudes.
- To estimate the monthly average daily conversion factors, ($\overline{H}_T/\overline{H}$), for global radiation in various provinces of Thailand.

Input requirements of a computer programme to estimate all of the items above consist of the following information:

(i) Climatic data from measurement at the design location (a case study for Thailand), total daily global irradiation and monthly average daily global irradiation on the horizontal surfaces.

(ii) An isotropic model of the sky from Liu and Jordan.

(iii) The equations of correlation for beam and diffuse components of daily and monthly radiation from Erbs et al.

3.5 Results and Discussions

In the present study the total solar radiation on tilted surfaces on various slope angles for selected provinces of Thailand, situated at a latitude between 6° and 20° N has been calculated based on the isotropic model. The present study's results can be addressed as follows. Firstly, the ratio of the average daily beam radiation on the tilted surface to that on the horizontal surface for the month ($\overline{R}_b$) has been computed. That is a function of transmittance of the atmosphere and has been also plotted as a function of latitude between 6° and 20° N for a surface that is sloped toward the equator with $\gamma = 0°$ as shown in Figure 3.4. It shows the value of $\overline{R}_b$ of each month is a little different, especially the latitudes that are lower than 8° N. However, they have shown that the effects of sloping to the south for $\overline{R}_b$ throughout the winter (Nov.-Jan.) are larger than other months of the year. On the other hand, the values of $\overline{R}_b$ in the summer (May-June) are least. Secondly, the monthly average daily total radiation on the tilted surfaces ($\overline{H}_T$) for selected provinces of Thailand has been estimated. The annual variation of global radiation on horizontal and tilted surfaces for 4 provinces that are different latitudes and compass points have been plotted. In fact, Chiang Mai (18.78°N) is in the north and Roi Et (16.05°N) is in the north-east. Bangkok (13.73°N) and Phuket (7.88°N) are in the central part and in the south respectively. They are shown in Figures 3.5 through 3.8. Altogether, they show the values of $\overline{H}_T$ for different surface orientations and the values that are reported in these figures are expressed in kWh/m^2. Due to the fact that no information is available about the ground-reflectance (albedo), ρ_g is assumed to be 0.20 as suggested by Liu and Jordan [11,16]. Figure 3.9 shows variation of average annual radiation, winter (Nov.-Jan.) and summer (May-July) as a function of surface slope for Songkhla province. It indicates a maximum average annual radiation at approximately $\beta = 7°$. It also shows a maximum average seasonal radiation in the winter for the months of November, December and January. The slope corresponding to the maximum estimated is about 32°. On the other hand, a maximum point of average seasonal radiation in the summer for the months of May, June and July is about -18°. Furthermore, the variation of average annual and seasonal radiation for other provinces of Thailand was calculated.

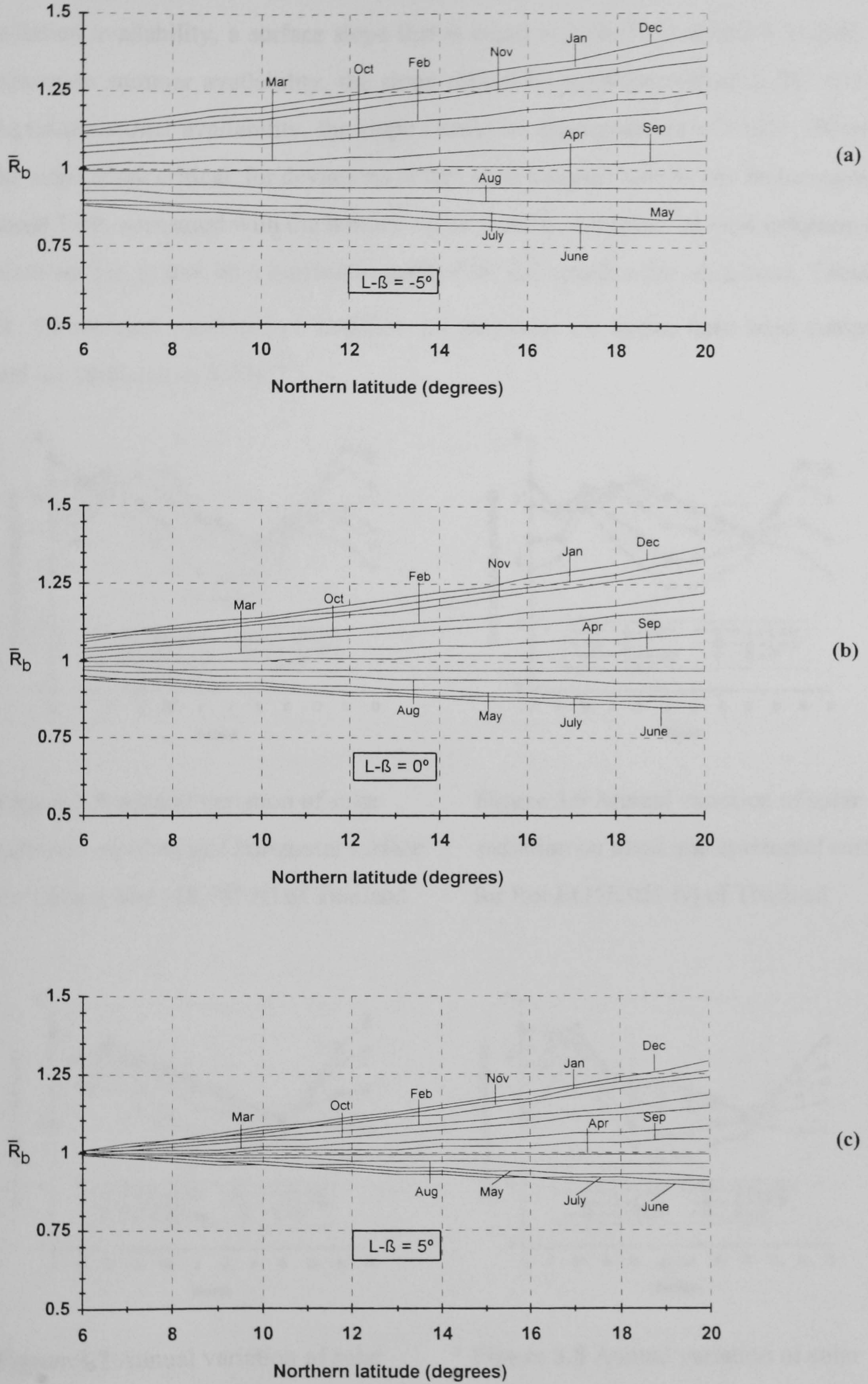

Figure 3.4 (a) $\bar{R}b$ as a function of various latitudes for L-ß = -5°
(b) for L - ß = 0° and (c) for L - ß = 5°

Considering the results it can be concluded that for the maximum average annual radiation availability, a surface slope that is equal to latitude in question is best. For maximum summer availability, the slope should be approximated as L-25° and, for maximum winter availability, the slope should be approximated as L+25°. However, the slope is not critical, for deviations of 25° from latitude, energy can be increased by about 7-8% compared with the latitude value. Finally, the ratios of total radiation on a tilted surface to that on a horizontal surface for the month were calculated. Values of $\bar{R}$, for selected provinces of Thailand, for particular tilt angles have been computed and are tabulated in Table 3.5.

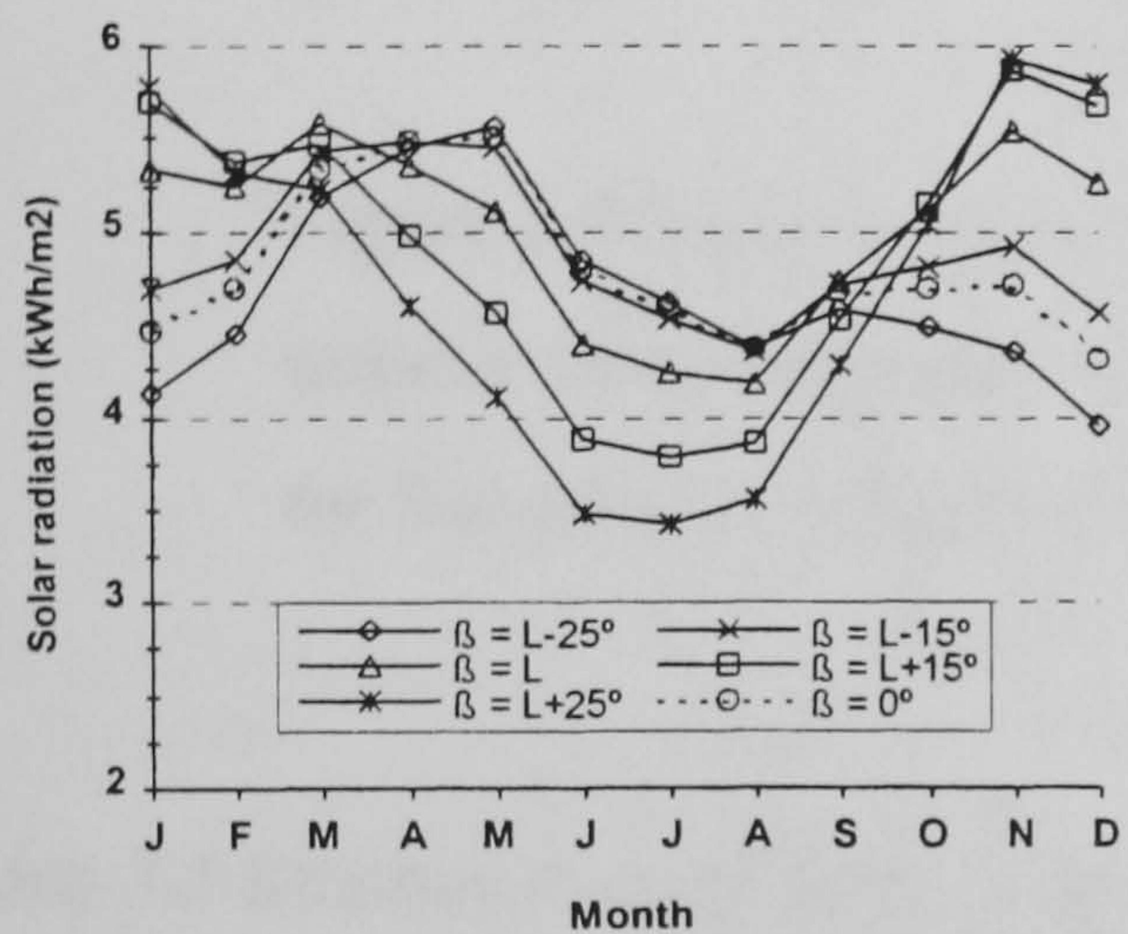

Figure 3.5 Annual variation of solar radiation on tilted and horizontal surface for Chiang Mai (18.78° N) of Thailand

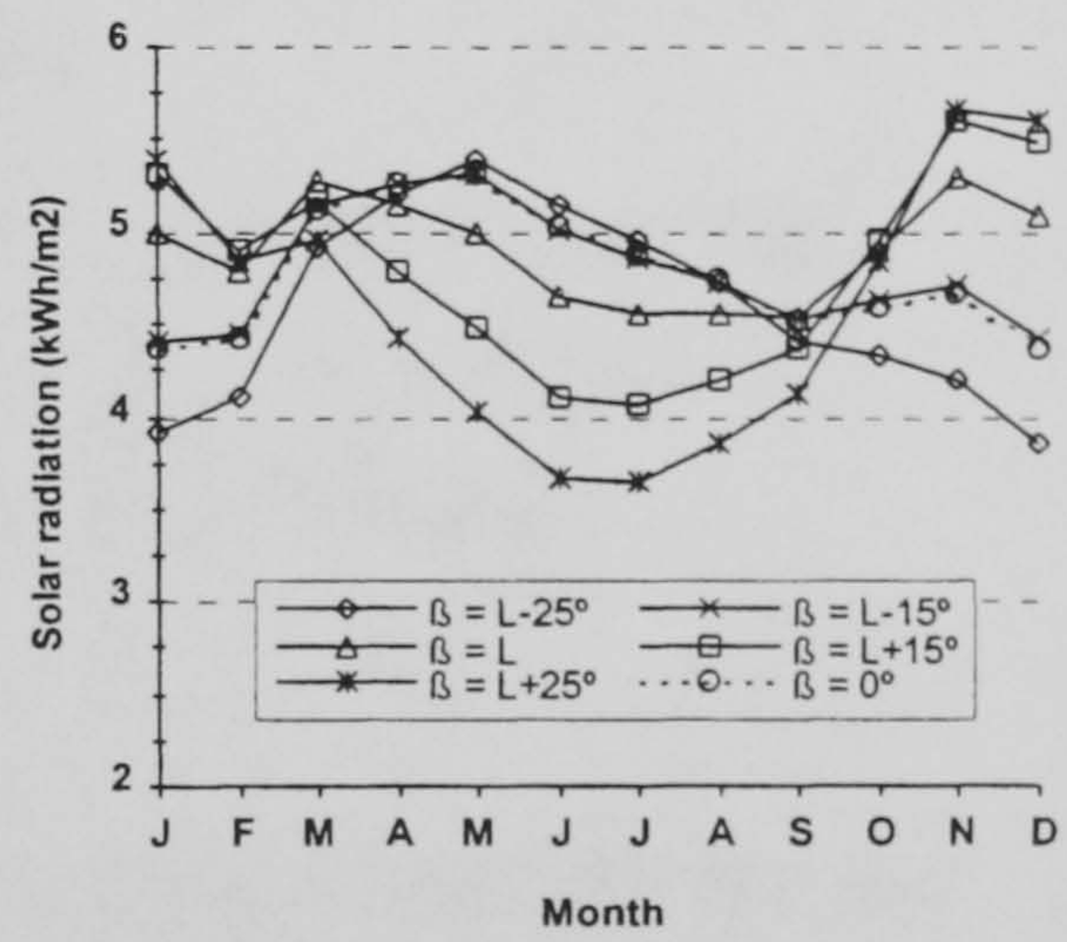

Figure 3.6 Annual variation of solar radiation on tilted and horizontal surface for Roi Et (16.05° N) of Thailand

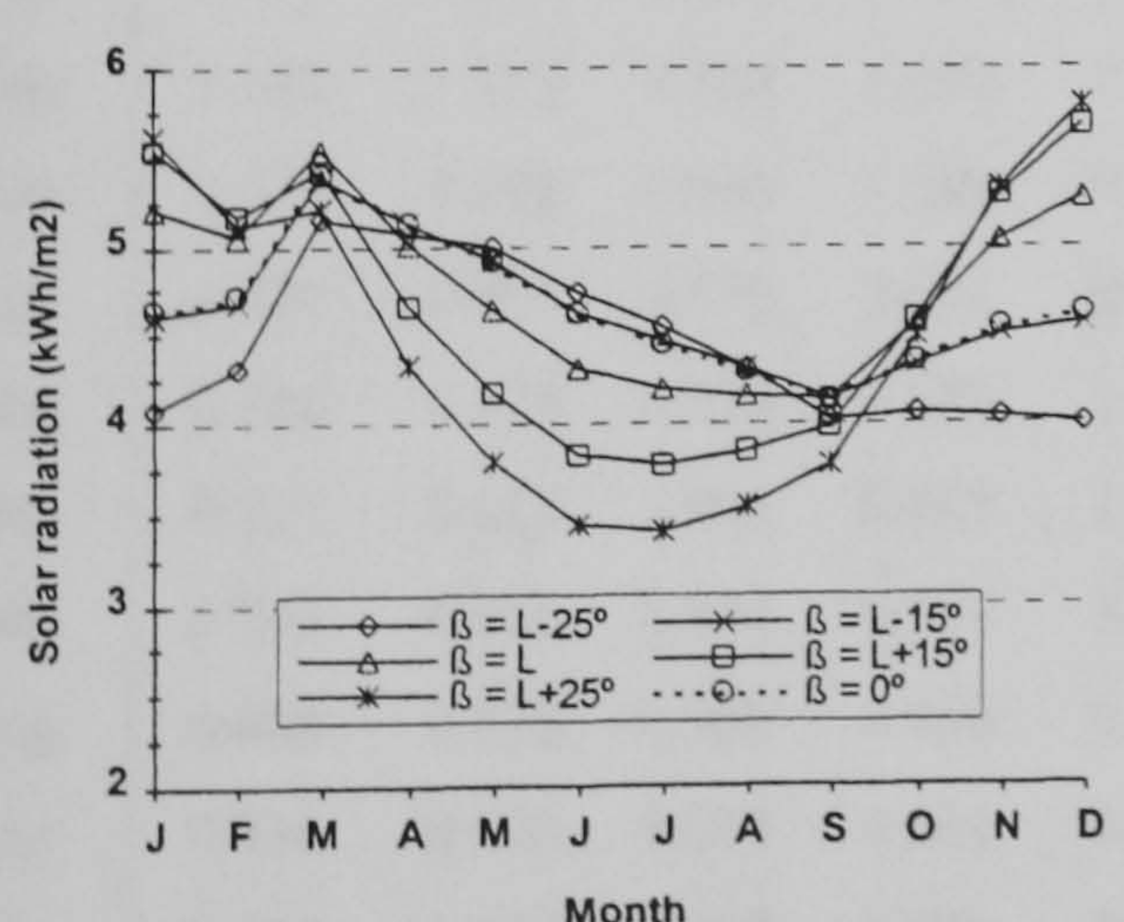

Figure 3.7 Annual variation of solar radiation on tilted and horizontal surface for Bangkok (13.73° N) of Thailand

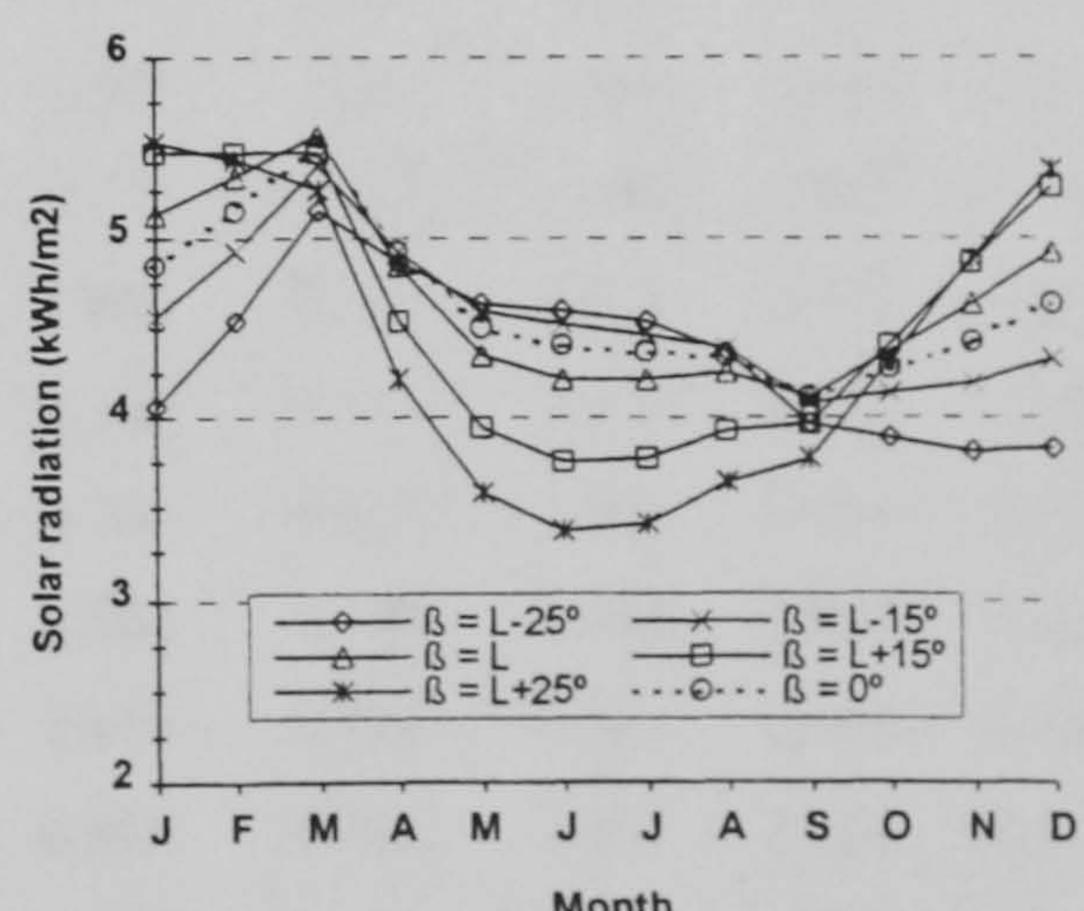

Figure 3.8 Annual variation of solar radiation on tilted and horizontal surface for Phuket (7.88° N) of Thailand

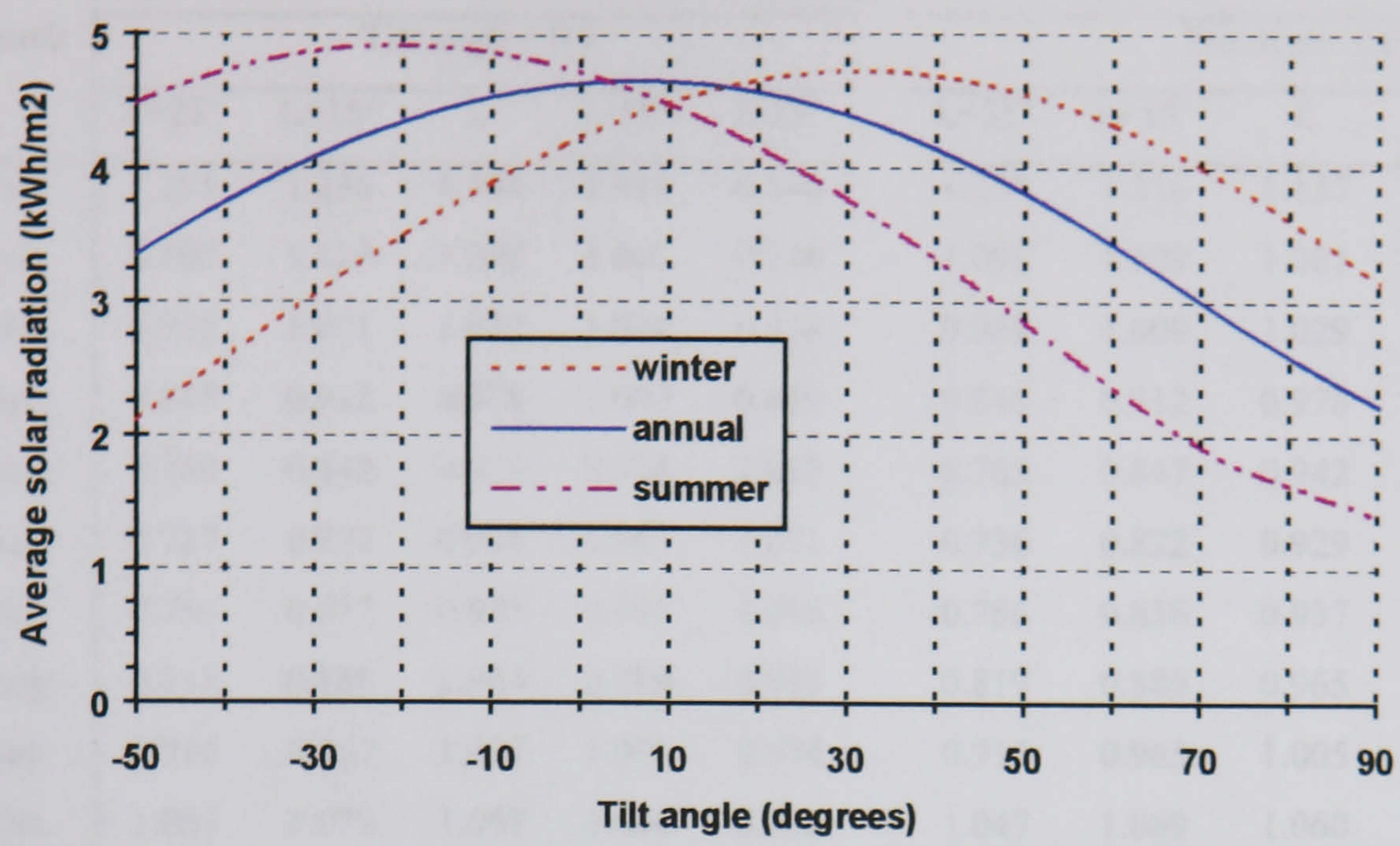

Figure 3.9 Variation of average annual, winter (Nov.-Jan.) and summer (May-July) solar radiation as a function of tilt angles for Songkha (L = 7.23°, $\gamma = 0°$, $\rho_g = 0.20$) of Thailand

Table 3.5 Monthly average daily conversion factor (ratio of total radiation on a tilted surface to that on a horizontal surface ($\overline{H}_T/\overline{H}$)) for selected provinces of Thailand (where $\gamma = 0°$).

Month	Chiang Rai (19.88° N)					Loei (17.45° N)				
	Tilt angle (β)					Tilt angle (β)				
	L+25°	L+15°	L	L-15°	L-25°	L+25°	L+15°	L	L-15°	L-25°
Jan.	1.300	1.284	1.203	1.060	0.935	1.247	1.232	1.156	1.022	0.906
Feb.	1.140	1.153	1.124	1.040	0.955	1.109	1.122	1.095	1.015	0.934
Mar.	0.979	1.022	1.046	1.020	0.975	0.971	1.013	1.034	1.007	0.963
Apr.	0.837	0.906	0.976	1.002	0.993	0.846	0.912	0.978	1.000	0.990
May	0.746	0.829	0.928	0.989	1.006	0.763	0.844	0.938	0.995	1.010
Jun.	0.727	0.811	0.914	0.985	1.011	0.741	0.824	0.926	0.994	1.017
Jul.	0.745	0.826	0.924	0.987	1.008	0.758	0.838	0.934	0.995	1.013
Aug.	0.808	0.879	0.958	0.996	0.999	0.819	0.888	0.963	0.998	0.999
Sep.	0.916	0.970	1.014	1.011	0.984	0.915	0.966	1.007	1.004	0.977
Oct.	1.075	1.100	1.092	1.031	0.963	1.048	1.072	1.066	1.011	0.948
Nov.	1.253	1.245	1.180	1.054	0.941	1.200	1.194	1.135	1.019	0.916
Dec.	1.348	1.323	1.226	1.066	0.929	1.283	1.260	1.172	1.024	0.899

Table 3.5 (Continued)

Month	Khon Kean (16.45° N)					Ubon Ratchathani (15.25° N)				
	Tilt angle (β)					Tilt angle (β)				
	L+25°	L+15°	L	L-15°	L-25°	L+25°	L+15°	L	L-15°	L-25°
Jan.	1.255	1.236	1.154	1.011	0.890	1.234	1.216	1.137	1.000	0.883
Feb.	1.107	1.119	1.090	1.007	0.926	1.098	1.109	1.081	1.000	0.920
Mar.	0.970	1.011	1.032	1.004	0.958	0.969	1.009	1.029	1.000	0.954
Apr.	0.845	0.912	0.978	1.000	0.989	0.846	0.912	0.978	1.000	0.989
May	0.760	0.842	0.939	0.998	1.013	0.765	0.847	0.942	1.000	1.014
Jun.	0.737	0.822	0.926	0.997	1.021	0.736	0.822	0.929	1.000	1.025
Jul.	0.755	0.837	0.935	0.997	1.016	0.756	0.838	0.937	1.000	1.019
Aug.	0.818	0.888	0.964	0.999	0.999	0.819	0.889	0.965	1.000	1.000
Sep.	0.916	0.967	1.007	1.002	0.974	0.915	0.965	1.005	1.000	0.972
Oct.	1.057	1.079	1.068	1.006	0.938	1.047	1.069	1.060	1.000	0.934
Nov.	1.226	1.213	1.142	1.011	0.896	1.200	1.190	1.124	1.000	0.891
Dec.	1.304	1.275	1.175	1.013	0.878	1.278	1.251	1.155	1.000	0.871

Table 3.5 (Continued)

Month	Chanthaburi (12.60° N)					Songkhla (7.23° N)				
	Tilt angle (β)					Tilt angle (β)				
	L+25°	L+15°	L	L-15°	L-25°	L+25°	L+15°	L	L-15°	L-25°
Jan.	1.198	1.182	1.109	0.980	0.870	1.123	1.111	1.047	0.935	0.839
Feb.	1.075	1.088	1.063	0.987	0.911	1.050	1.059	1.030	0.953	0.878
Mar.	0.958	0.999	1.020	0.994	0.950	0.955	0.992	1.009	0.977	0.931
Apr.	0.849	0.914	0.979	1.000	0.990	0.861	0.924	0.986	1.004	0.990
May	0.781	0.859	0.951	1.005	1.017	0.794	0.875	0.969	1.023	1.033
Jun.	0.762	0.843	0.942	1.006	1.027	0.766	0.854	0.962	1.032	1.053
Jul.	0.779	0.857	0.948	1.005	1.021	0.779	0.864	0.965	1.028	1.044
Aug.	0.834	0.900	0.970	1.002	1.000	0.835	0.905	0.980	1.012	1.007
Sep.	0.912	0.960	1.000	0.997	0.972	0.919	0.965	0.999	0.989	0.958
Oct.	1.023	1.047	1.042	0.990	0.931	1.007	1.027	1.019	0.966	0.908
Nov.	1.158	1.152	1.094	0.982	0.883	1.087	1.084	1.038	0.945	0.863
Dec.	1.240	1.215	1.125	0.977	0.855	1.135	1.118	1.049	0.933	0.836

Table 3.6 Monthly average daily solar radiation on a tilted surface at latitude angle (17° N) for Udon Thani province of Thailand (where $\gamma = 0°$).

Month	$\bar{H}$	$\bar{H}_o$	$\bar{K}_T$	$\bar{H}_d/\bar{H}$	$\bar{R}_b$	$\bar{H}_T$	R
Jan.	4.558	7.875	0.579	0.357	1.265	5.318	1.167
Feb.	4.341	8.842	0.491	0.438	1.172	4.738	1.091
Mar.	4.135	9.844	0.420	0.511	1.069	4.247	1.027
Apr.	4.850	10.565	0.459	0.470	0.969	4.742	0.978
May	4.348	10.815	0.402	0.532	0.896	4.105	0.944
Jun.	4.770	10.822	0.441	0.489	0.864	4.407	0.924
Jul.	4.115	10.775	0.382	0.555	0.878	3.860	0.938
Aug.	3.910	10.606	0.369	0.571	0.937	3.773	0.965
Sep.	4.375	10.062	0.435	0.495	1.028	4.409	1.008
Oct.	4.318	9.101	0.474	0.454	1.137	4.617	1.069
Nov.	4.096	8.081	0.507	0.423	1.240	4.643	1.133
Dec.	4.178	7.568	0.552	0.381	1.293	4.919	1.177

3.6 Summary

A method based on an isotropic model by Liu and Jordan has been used to estimate the solar radiation on an inclined surface for Thailand, situated at latitudes between 6° and 20° N. The monthly average daily total radiation on the tilted surfaces (H_T) for selected provinces has been estimated. The optimum tilt angles in different seasons for summer and winter for Thailand are approximately latitude minus 25° and latitude plus 25° respectively. Among all the inclinations studied here, a tilt angle that is equal to latitude at the design location will collect the maximum energy round the year. The ratio of the monthly average daily total radiation on the tilted surfaces to that on the horizontal surfaces (H_T/H) for selected provinces has been computed. These results come from the outcome of a computer programme and a flow chart of the programme is shown in appendix B. Furthermore, the significant figures of the solar altitude angle and the solar azimuth angle in appendix A are useful data for anywhere that is situated between latitude 6° and 20° N. Thus a PV array should be tilted at the latitude angle for best static performance throughout the year. In addition, the monthly average daily total radiation on the south-facing surfaces on various tilted angles (0°- 90°) for selected provinces of Thailand from the outcome of the computer programme have been provided in appendix A. The results that are presented here can provide a useful reference of radiation data on inclined surfaces for the future solar energy and PV system applications in Thailand. They should be applicable in other countries that are located with the same latitude angle and a similar climate.

3.7 References

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Chapter 4

Design and Analytical Evaluation of a Centralised PV Mini-Grid System

Chapter 4

4.1 Introduction

Rural electrification is one of the main applications of PV power systems. Stand-alone PV generators are suitable for use in rural households or villages that are located far away from the national utility grid. Since extension of the grid system into rural villages is expensive, especially in developing countries, PV systems offer a cost-effective alternative for rural electrification of remote villages. Thailand is a country where there are many rural villages and approximately 265,000 households in 1998 [1] have no access to electric power. Rural people use kerosene lamps and candles for lighting applications. There are no facilities for community entertainment. In some areas the roads are in poor condition and the transportation of necessary goods and humans is a problem. However, access to electricity is a key element in determining quality of life and many of these people would appreciate the convenience of electricity. Stand-alone PV power systems are a viable solution and a valid alternative source of energy in rural areas of Thailand. They are referred to as autonomous systems that operate independently of the national utility grid. One approach to electrifying such a village is a centralised PV mini-grid system, supplying individual households and a community centre in the village through a local mini-grid system. Another type of stand-alone PV system is a decentralised system such that each household can use the electrical loads, such as lamps, radio and a TV set with an individual PV/battery system. Decentralised stand-alone PV systems are also used for water pumping, public lighting, vaccine refrigeration, solar home systems as well as battery charging station systems.

This chapter will focus on the design and analytical evaluation of a centralised PV mini-grid system, a case study in a Thai rural village, according to the daily load requirement in the village. The Balance of the Systems (BOS) has been designed. An economic analysis of the system has been also studied. Methodical analysis in this study provides a useful example as an optional design of PV systems in the village for electrification planners or PV engineers to consider for installation.

4.2 Assessment of the Daily Load Requirements in a Thai Rural Village

4.2.1 General Considerations

The first step of the design is to determine daily load demand in each household. The design approach is the calculation of an array sizing based on climatic data at the design location, efficiency of system parameters, performance rated output of solar modules and so on. A typical rural village in developing countries needs a basic load, such as lamps, radio, a TV set, water pumping and vaccine refrigeration systems [2-5]. Accordingly, the daily electrical energy needs of a village for this study can be broadly split into three categories, namely household, a community centre and public use. In addition, a load profile of the village for each hour is one of the important data sets for the design of a stand-alone PV power system. Four load profiles have been selected for analysis, namely:

(i) night time loads, e.g., indoor lighting, street lighting and a TV set.
(ii) daytime loads, e.g., water pumping.
(iii) constant load demand, e.g., refrigeration.
(iv) variable load demand, e.g., radio

Load profiles should be collected from the end-users in the village [6]. Nevertheless, energy users do not always have a good understanding of energy costs and energy consumption. Part of the energy needs assessment is to inform users about the options and the associated costs. The selection of system voltage and the alternating current (AC) or direct current (DC) loads mainly depends on a number of limitations as follows [3,6].

(1) In DC load

- In a small PV system or low power stand-alone PV applications, DC loads should be selected. This is because the vast majority of DC appliances operate at 12 volts and power losses can be reduced, due to the fact that there is no an inverter. They can also operate at 24 volts. Higher voltage DC appliances are less readily available. DC loads consist of resistive, constant current and voltage, or constant power in the applied range. Typical DC loads are lamps, radios, a TV set and refrigerator/freezer.

- The cable power losses will depend on currents that flow through the cable or electric wire. The power loss is proportional to square of the current (I^2). The size of the cables and length should be closer so that the voltage drop over cables is less than 3%.
- Maximum current per circuit should normally be limited to 20 amps. The total current should not exceed 100 amps if separate circuits are used. It is recommended that single circuits should be limited to about 240 W at 12 V, 480 W at 24 V or 720 W at 36 V. The total power drawn should be limited to about 1.2 kW, 2.4 kW or 3.6 kW respectively, if multiple circuits are used [3].

The selection of the DC bus voltage level is influenced by the following considerations: (i) use of standard commercially available equipment, including motors and inverters, (ii) input voltage requirements of the user equipment and (iii) minimization of distribution wire size and I^2R losses. Based on the lessons learned, for a PV array sizing of no more than 10 kW, the bus voltage should not normally exceed 120 VDC. For a sizing between 10 and 100 kW, a DC bus voltage of 240 VDC has proven to be adequate. For higher power levels, 600 VDC appears to be a practical limit due to switching gear cost and availability [6].

(2) In AC system

The selection of nominal system voltage (or battery voltage) depends mainly on the peak power demand and on the choice of an inverter that is most suitable for meeting this demand. However, Sandia National Laboratories (USA) suggest the following guidelines [7].

Table 4.1 Nominal system voltage recommended by Sandia National Laboratories.

AC power demand	Inverter input voltage (battery voltage)
1.5 kW	12 VDC
1.5 - 5 kW	24 or 48 VDC
over 5 kW	48 VDC or higher

In general, a lower voltage inverter will draw very high currents at high power demands. Higher voltage inverters are capable of higher efficiencies. The conventional utility grid supply for Thailand is sinusoidal waveform at 50 H_Z. The vast majority of electrical appliances in each household and industries are designed to operate from an AC supply. Thus, standard AC appliances are more widely available than DC appliances. It is very easy to change AC voltage level by using transformers and this is the main reason why AC is widespread. It is strongly recommended that a long distance system should operate with an AC system since transmission loss can be reduced at high voltage. High transmission voltage typically operates at 220 volts for single phase load and 380 volts for three phase load. Nevertheless, there are a number of limitations in a DC system. Namely, the user is unable to use off-the-shelf AC appliances. Choice is reduced and service or replacement parts for DC appliances may be more difficult to access than for AC appliances (standard appliances), if the system is installed far from utility grid or installed in rural areas. Furthermore, most appliances will have to operate off the same voltage. When high voltage is required, such as in fluorescent lamps or in TV sets, each appliance needs and electronic circuit to achieve this. In the case of DC appliances which have a different operating voltage from the nominal system voltage, a special DC-DC converter may be required.

4.2.2 Daily Load Profile Assessment

The details of load profiles in the rural villages of Thailand depend mainly on the number of households, social and economic impact, and type of electrical appliances. However, a sample village with 100 households in a rural area of Thailand is selected for the design in this study. Daily load requirements are as follows:

a) *Initial Data*

- number of households — 100 households

(Average number of people per household is 5. This figure will be used for design of a PV pumping system in chapter 5)

- battery voltage level (DC bus voltage) — 240 VDC
- load voltage level (AC side) — 220 VAC
- frequency of system — 50 H_Z

b) *Daily Load Demand*

- for each household

one fluorescent lamp, 8 W	daily use	3	hours/day
one fluorescent lamp, 18 W	daily use	6	hours/day
one radio, 10 W	daily use	2	hours/day

- for a community centre

one refrigerator/freezer, 320 W	daily use	10	hours/day
six fluorescent lamps, 36 W	daily use	5	hours/day
one television set, 120 W	daily use	5	hours/day
one video cassette recorder, 40 W	daily use	5	hours/day

- for a control room housing

four fluorescent lamps, 36 W	daily use	5	hours/day
measuring devices and systems, 200 W	daily use	24	hours/day

- for public use

one pump/motor, 600 W	daily use	8	hours/day
twenty LPG sodium lamps, 26 W	daily use	5	hours/day

c) *Daily Load Timing*

Table 4.2: Daily load timing of PV electrification in a sample village

Load	hours / day	using time expected
F. lamp 8 W	3	18.00-23.00 (average 3 h)
F. lamp 18 W	6	05.00 - 06.00 18.00 - 23.00
F. lamp 36 W	5	18.00-23.00
Radio	2	18.00-23.00 (average 2 h)
LPG sodium lamps	6	05.00-06.00 18.00 - 23.00
Television	5	18.00 - 24.00
Video Cassette Recorder	5	18.00 - 24.00
Refrigerator/Freezer	10	average 10 h
Water Pumping	8	08.00-16.00
Measuring systems	24	00.00-24.00

(d) Electrical Energy Requirements for Electricity

Table 4.3: Electrical energy requirements in a sample village

Appliances	Quantity	Power (W)	h/day	Wh/day	Remarks
FL small	100	8	3	2,400	loads for each household
FL medium	100	18	6	10,800	
Radio/tape	100	10	2	2,000	
FL large	6	36	5	1,080	loads for a community centre, a school
Television	1	120	5	600	
VCR	1	40	5	200	
R/F	1	320	10	3,200	
FL large	4	36	5	720	loads for a control room-housing
Meas. systems	-	200	24	4,800	
LPG sodium	20	26	6	3,120	loads for public use
Pumping	1	600	8	4,800	
Total watt-hours/day = 33,720					

FL = Fluorescent Lamp   VCR = Video Cassette Recorder
R/F = Refrigerator/Freezer   LPG = Low Pressure Gas

Since all loads in the table are AC appliances, in practice, the efficiency of power conversion produced by all passive components in AC circuit must be considered. Thus, in the case that the efficiency of power conversion is 85%, the total correct energy demand in the table must become approximately 39,670 Wh/day. This is an electrical energy that needs to be produced from the PV array.

e) *Hourly Energy Requirements*

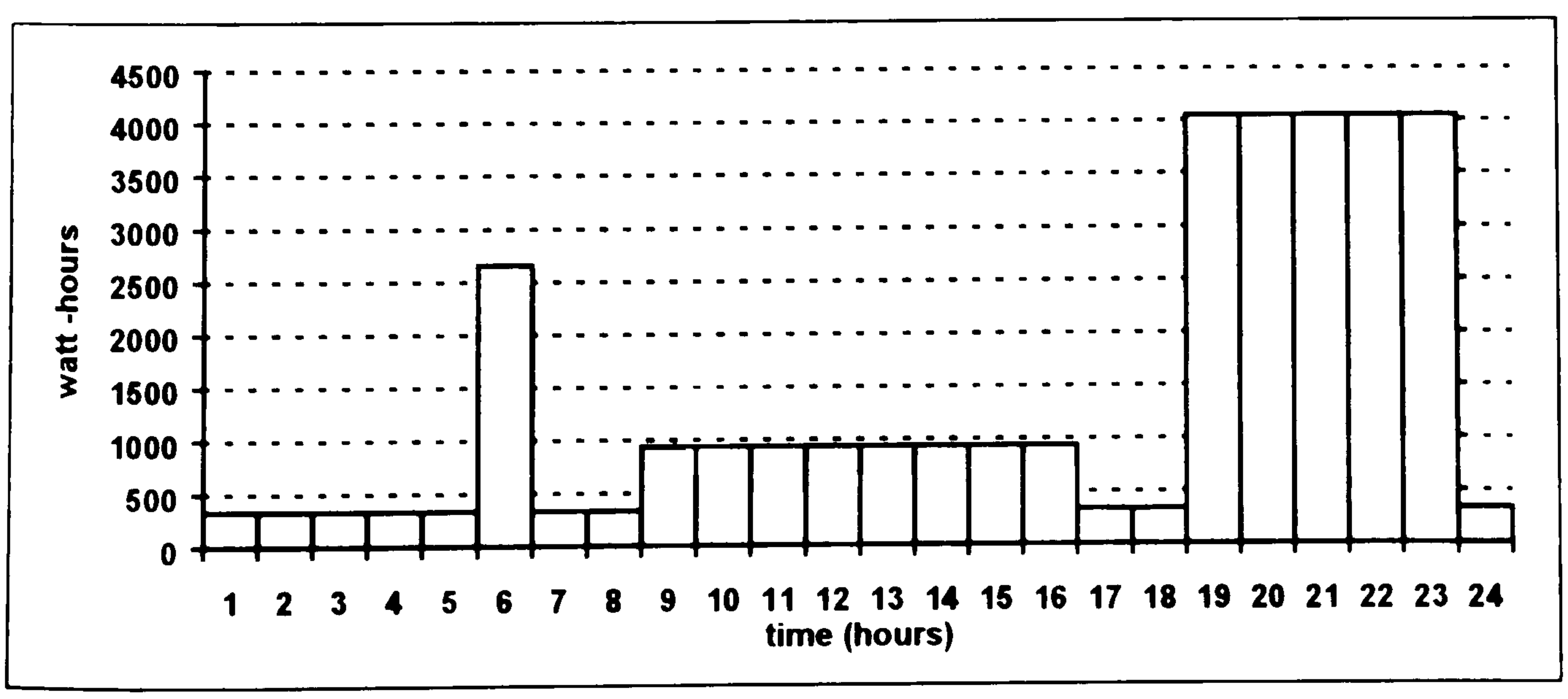


Figure 4.1 Hourly energy demand of PV electrification in a sample village

4.3 Sizing of Stand-Alone PV Power Systems

Sizing means calculating the size of PV array and storage battery required to supply the critical loads, during the worst climatic conditions. The calculation requires an estimate or record of the load demand and the irradiation profile for the application. A PV system sizing consists of working out the cheapest combination of array size and storage capacity that will meet the anticipated load requirements with the minimum acceptable level of security. By "security" is meant the probability that the system will always satisfy the load [8]. The fact that an over-sized PV/battery system can be expensive to install. An under-sized system will not deliver the power required, with the desired regularity, and may also lead to excessive battery discharge, shortened battery life and higher operating costs. Accurate PV system sizing is therefore important. The energy supply capacity of a PV/battery system depends on the size of the PV array and the size of storage battery. The general aims of PV sizing are:

- to determine the best matching between the PV array's size and the size of storage battery based on the climatic data at the design location, which will support the design load, at a chosen level of confidence, through expected weather conditions.
- to ensure efficient matching of components
- to provide a battery cycling environment that will help to get good service life from the batteries.

In practice, it is often hard to tell if an installed PV system has been under or over-sized. If a PV system is over-sized for the design load, the effect will not be easily detected. One symptom is that batteries spend much of their time at float charge, even in below average weather, but it would take a long period of monitoring to determine whether the system was over-sized even for exceptionally bad weather conditions. An over-sizing of the system will lead to inflated system costs [9]. An under-sized system will lead to an unacceptable number of system failures and the symptoms are repeated failure to deliver the power required, and prolonged undercharging of the batteries. Other factors could lead to the same problems, for example excessive load demand relative to the design load, poor matching of components in the system, unsuitable battery regulation, degradation of the array or the battery. Because of these difficulties in diagnosing faults in system sizing in the field, the designers may not gain reliable feedback about whether they are sizing systems correctly. As a result, a computer programme for determination of the best matching between the size of PV array and the size of the storage battery should be used. That predicts the system performance of a PV system designed over a yearly time scale (the details of this computer programme will be addressed in the next topic). The climatic data from many years will be exactly used to be an input of a computer program. The size of PV array and the size of the storage battery are also included. The designers normally need to use the data of solar irradiation on inclined surfaces from the measurement over several years for the design a PV system. Unfortunately, these data in Thailand are rare because only a few stations measure the solar irradiation on inclined surfaces. However, they can be estimated by theoretical models that have provided the results in chapter 3 and appendix A.

The minimum size of PV array depends mainly on the climatic data at the design location, I-V characteristics of the solar modules, data of daily load requirements and system parameters. The system parameters include the efficiency of system components, such as battery efficiency, regulator efficiency, inverter efficiency, modules mismatch efficiency and line loss factor efficiency. The array must be sized on the basis of the power it provides during the least sunny period of system operation. This should exceed, by a margin of 10% to 40%, the average total loads plus any inefficiencies in the controllers, battery and wiring [9]. There is a wide range of modules available for PV systems. The differences between them are in the number of cells, the size of each cell and the type of silicon used. When choosing a module for a PV system, there are main five questions to answer [10]: (i) Is there a local manufacturer of solar modules used?, (ii) Is a charge regulator going to be used in the system?, (iii) Is a blocking diode required?, (iv) Which modules are suitable for the average temperature at the site?, and (v) How can suitable modules be compared to find which represents best value for money at local prices?. Based on these questions, a BP solar module # BP 585 (monocrystalline silicon) with 36 series cells connected is selected for this research study with the suitable reasons as follows:

- there is a BP solar module's local manufacturer in Thailand.

- a maximum voltage of 16 V is required from a solar module in order for a 12 V battery to be fully charged through a blocking diode. By using modules with more than 32 cells, the maximum charging is maintained at 16 V and the battery reaches full charge in the shortest time.
- Most diodes are made of silicon so have a voltage drop of 0.7 V. Extra cells are needed to compensate for this voltage drop. Most charge-regulating units prevent battery discharge through a module at night by a diode or some sort of switch. Therefore a separate blocking diode is not usually required when a charge-regulating unit is used. However, for large scale systems the separate blocking diodes for each string should be used to prevent the currents flow back from battery.
- In hot areas where the average temperatures are higher than 20°C ,such as Thailand, the cells may operate at a much higher temperature than 50°C under full sun. This reduces the voltage of the whole module. To compensate for this drop in voltage, more cells are needed. A solar module with more than 34 cells is recommended (see Table 4.4).
- The number of single-crystal silicon cells needed in a module depends on the type of charge regulation to be used and the local temperatures. Modules with more than 34 cells and a charge regulator make better use of the available sunshine to charge batteries in the shortest time [10]. Extra cells are needed in hot climates and in systems with large system losses to the batteries. Module can also be selected according to their open circuit voltage which is directly affected by the number of cells. The number of cells relates to the applications are summarized in Table 4.4.

Table 4.4 Selection of a module for various system types and climates based on open circuit voltage in volts (V_{OC}) under standard test condition (STC) or number of cells in the module (STC: 1 kW/m^2, AM 1.5, and 25°C [10]

Applications	Local climate			
	Mild (usually below 30°C at midday)		Hot (usually above 30°C at midday)	
	Crystalline silicon	Thin-film silicon	Crystalline silicon	Thin-film silicon
self-regulating no diode	18 V (30 cells)	20 V	19 V (32 cells)	21 V
self-regulating with diode	19 V (32 cells)	21 V	20 V (34 cells)	22 V
with a charge regulator	≥ 20 V (>32 cells)	≥ 22 V	≥ 21 V (>34 cells)	≥ 23 V

4.3.1 Calculation of the PV Array Size

The design of array size of a large PV system must take into account various factors. They are mean annual global irradiation, I-V characteristics of a solar module, daily load requirement in ampere-hours or kWh, battery efficiency, module mismatch efficiency, regulator efficiency, inverter efficiency and the efficiency or line loss factor of system. Even though the climatic data from nearest stations or a similar climate zone can be used, they need to be modified through a "variability factor" to allow for the variation from year to year both in the mean and worst case values. By taking a large variability factor of 10% to 15% [11], it is a possible to work with average monthly solar irradiation.

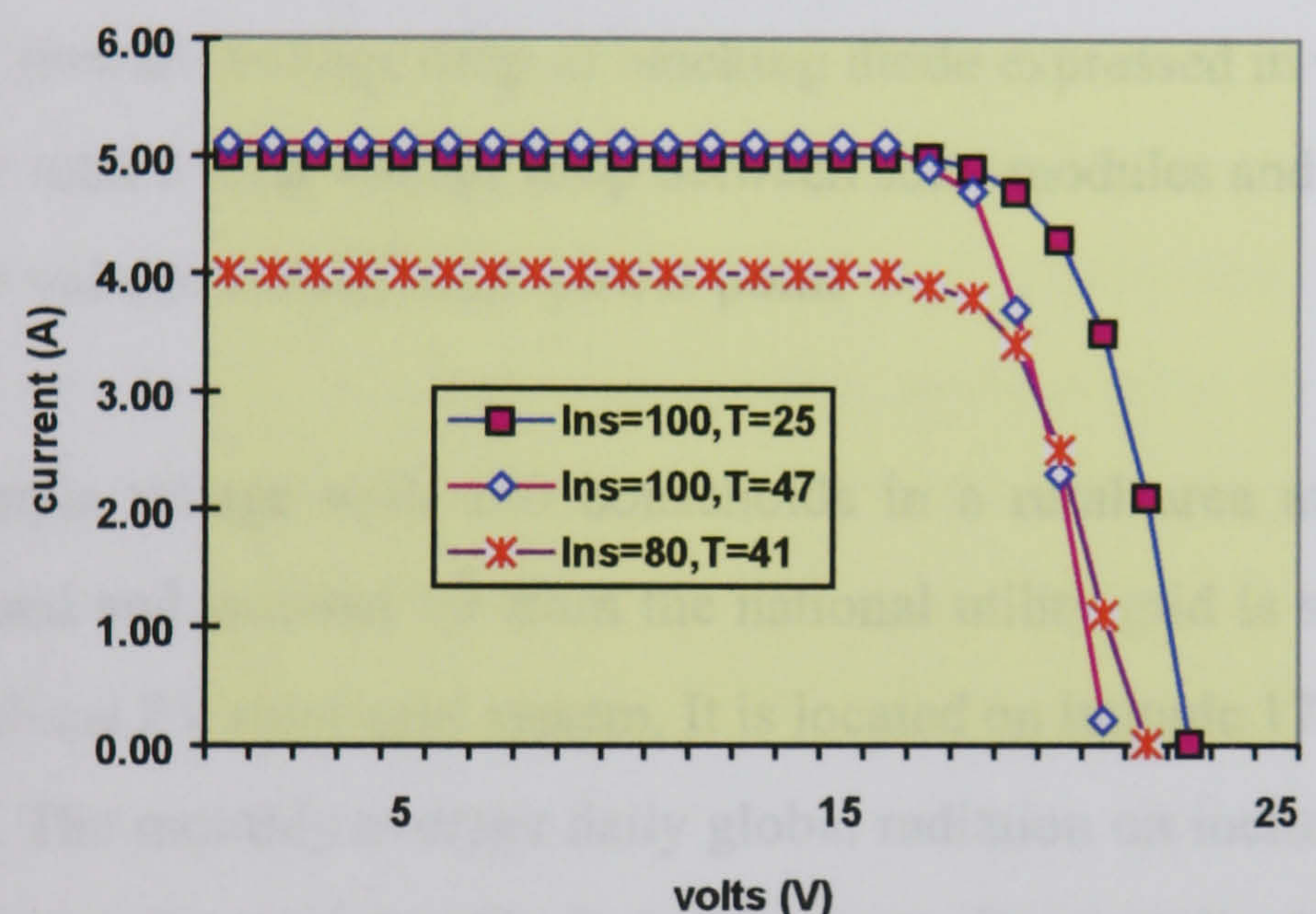


Figure 4.2 I-V characteristic curve of a BP solar module # BP585

The minimum array size that can meet the load requirements can be written as:

$$N_A = (N_S \times AH_{(load)} \times \varnothing) / (K \times VF \times A_M \times D_M) \quad (4.1)$$

$$K = \eta_B \times \eta_M \times \eta_L \times \eta_R \times \eta_I \quad (4.2)$$

where :

N_A = total number of modules connected in a PV system

N_S = number of modules connected in series in a string

$AH_{(load)}$ = daily energy requirement in ampere-hours.

$\varnothing$ = solar radiation intensity for testing of a module in kW/m^2.

VF = variability factor specified expressed in decimal

A_M = rated current of a module under STC in ampere

D_M = solar irradiation in $kWh.m^{-2}.day^{-1}$

The following factors are included in decimal format,

η_B = battery efficiency

η_M = module mismatch efficiency

η_L = line loss factor

η_R = regulator efficiency

η_I = inverter efficiency

and

$$N_S = (V_B + V_F + V_W) / V_{mp} \tag{4.3}$$

where

V_B = nominal battery bus voltage expressed in volts

V_F = forward voltage drop of blocking diode expressed in volts

V_W = total wiring voltage drop between solar modules and battery expressed in volts

V_{mp} = voltage at maximum power point

A sample village with 100 households in a rural area at Udon Thani province of Thailand and isolated far from the national utility grid is selected for the design of a centralised PV mini-grid system. It is located on latitude 17° 23′ N and longitude 102° 48′ E. The monthly average daily global radiation on inclined surfaces at Udon Thani province to be used for this design is shown in appendix A. This data is a result from the computer programme in chapter 3, and based on some tables in reference 12. These tables provide the global solar radiation for selected provinces of Thailand estimated from mean daily duration of sunshine in each 1½ month period at the 18 stations and sunshine averages over 15 to 20 years. Data for other provinces of Thailand can also be found in appendix A.

The data for Udon Thani province shows that the maximum value of annual average daily global radiation on tilted (inclined) surface is 4.481 $kWh.m^{-2}.day^{-1}$. It is indicated that PV array should be installed facing toward the equator for Thailand at the latitude angle to receive a maximum annual average daily global radiation. Furthermore, the maximum monthly average daily global radiation for this province at the latitude angle is about 5.317 $kWh.m^{-2}.day^{-1}$ in January and the minimum value is about 3.773 $kWh.m^{-2}.day^{-1}$ in August.

4.3.2 Calculation of the Battery Capacity

The battery is an essential part of most stand-alone renewable systems. In any PV system, it is impossible to separate the requirements for PV array sizing and battery sizing as both are necessarily dependent on each other. The battery should be sized to ensure that the PV system satisfies the user's requirements of reliability of supply and autonomy. Both over-sizing and under-sizing can result in unsatisfactory system performance. To date, due to competitive pressures in the PV industry, excessive over-sizing has not been a major problem with under-sizing prevalent [13,14]. Over-sizing means that the battery capacity is too large for the application. It is usually caused by one of the following: (i) over estimation of the load and (ii) under estimation of the available solar irradiation. A battery that is over-sized with respect to the system load will normally shallow cycle during the month of high radiation. Hence, the battery is always recharged from a high state-of-charge. The disadvantage of this cycling regime is that the charge acceptance of the battery at high state-of-charge levels is low and hence cycling efficiency is reduced. For the battery to reach full charge condition, a long period on float charge, with reduced array current, is required. This represents an inefficient use of the available solar energy. In some cases an auxiliary source of supply may be required to provide an equalizing or boost charge. In addition, under-sizing of a PV system is normally due to one of the following: (i) an excessive need to reduce system costs, (ii) design calculations with poor worst case estimates and (iii) an increase in energy consumption during system operation. During the month of high radiation, an undersized battery usually reaches full charge every day. It also supplies a large fraction of its capacity to the load on demand. The problems encountered with this arrangement are as follows: the battery can be overcharged daily where an excess of PV array output is available and not carefully regulated.

In the case of the month of low radiation, the effect of battery under-sizing on system performance can be severe. The principal problems encountered in these circumstances are (i) load autonomy during periods of low PV energy is very poor and (ii) long periods at low state of charge can result in plate sulphation which is irreversible. Clearly, an undersized battery in a PV system provides poor load reliability. This situation also subjects the battery to seasonal extremes of operation with excessive overcharging during high radiation. These operating conditions combine to accelerate battery degradation and reduce battery life.

The period of storage required should be based on the maximum number of consecutive days with rain or cloud. It depends on the latitude of location and the climatic data at the design location. A typical figure used in battery sizing of small systems at low latitude is five days, whereas ten or more days may be used for the latitude above 30° [6]. However, it is counterproductive to have a very large battery capacity if the array power is insufficient to recharge such a large battery adequately. Very high reliability could be obtained by over-sizing the array as well as the batteries. Several methods for calculating battery size have a limitation of the present sizing method in that they do not provide a way of calculating how much the array should be oversized. A computer programme was specifically developed in this research to predict the best matching between the size of PV array and the size of the storage battery. Their outcomes can indicate how many days of battery storage are suitable based on daily global irradiation on tilted surfaces at the design location throughout the year.

The depth of discharge in one cycle depends on what the cell is being used for and is not always down to 0% state of charge. In fact, for any particular design of battery the dominant factor affecting cycle life is DOD, i.e. the proportion of capacity removed and replaced at each cycle. For a low DOD (<20%) the number of cycles remains predominantly the same (typically 1,000+). However as the DOD increases the number of cycles reduces significantly. In most PV applications the battery undergoes a daily discharge (typically less than 20%) and, besides this, a deeper annual discharge. This annual discharge is actually beneficial to the battery as it stimulates usage of the active material within the battery and does not adversely affect the number of cycles. Nevertheless, it is recommended that a typical type of battery used in PV system should not be discharged over 50% DOD of battery capacity [15]. There are a few types of battery which have been designed for using with deep discharge and recharge (typically 70%). To estimate the battery capacity for a centralised PV mini-grid system in the sample village, the following expression can be used [16]:

$$E_b = (x\, E_n + y\, E_d) / [\eta_L \times V_D \times (DOD/100)] \qquad (4.4)$$

$$x\, E_n = x_1 E_{(RADIO)} + x_2 E_{(LIGHTING)} + x_3 E_{(STREET\ LIGHTING)}$$
$$+ x_4 E_{(TV)} + x_5 E_{(VIDEO)} + x_6 E_{(R/F)} + x_7 E_{(MEASURING)}$$
$$+ \ldots + x_n E_{(OTHER\ LOADS)}$$

$$y\, E_d = y_1 E_{(RADIO)} + y_2 E_{(R/F)} + y_3 E_{(PUMPING)} + y_4 E_{(MEASURING)}$$
$$+ \ldots + y_n E_{(OTHER\ LOADS)}$$

where

E_b = the size of storage battery (bank) in ampere-hours

E_n = total energy of daily load demand during night time in watt-hours

E_d = total energy of daily load demand during daytime in watt-hours

$x_1, x_2, \ldots, x_n$ = days of autonomy which storage is to be provided for each load or appliances during night time in day

$y_1, y_2, \ldots, y_n$ = days of autonomy which storage is to be provided for each load or appliances during daytime in day

V_D = nominal battery voltage in volts

DOD = maximum permissible depth of discharge in percentage

4.4 PV System Sizing Using a Computer Programme

A computer programme was specifically developed with C-language and divided into 2 parts, namely, to compute system sizing and system performance [17-24].

4.4.1 The Sizing Procedure of a Centralised PV Mini-Grid System

The computer programme needs some factors to be an input to the source programme, such as daily load profile, specific data of climate at the site, system parameters, I-V characteristics of a solar module, days of autonomy for each load. These data can be seen from the results of this programme below. The design procedure consists mainly of the following steps:

- Input data
- Computation of load profile

  - total energy demand during daytime

  - total energy demand during night time
- Computation of the PV array size
- Computation of the storage battery capacity
- Computation of an inverter size and back up generator

4.4.1.1 The Input Data

no. of households in the village = 100.0 households
nominal system voltage = 240.0 VDC
lighting load per household = 8.0 W. quantity = 100.0
total no. of hours used for lighting load = 3.00 hours/day
lighting load per household (set 2) = 18.0 W. quantity = 100.0
total no. of hours used for lighting load (set 2) = 6.00 hours/day
lighting for community centre, etc., = 36.0 W. quantity = 10.0
total no. of hours used for lighting in a community centre = 5.00 hours/day
radio load = 10.0 W. quantity = 100.0
total no. of hours used for radio = 2.00 hours/day
radio is used during daytime = 0.00 hours
street lighting load = 26.0 W. quantity = 20.0
total no. of hours used for street lighting = 6.00 hours/day
TV load = 120.0 W. quantity = 1.0
total no. of hours used for TV = 5.00 hours/day
TV is used during daytime = 0.00 hours
video load = 40.0 W. quantity = 1.0
total no. of hours used for video = 5.00 hours/day
video is used during daytime = 0.00 hours
refrigerator load = 320.0 W. quantity = 1.0
total no. of hours used for refrigerator = 10.00 hours/day
pumping load = 600.0 W. quantity = 1.0
total no. of hours used for pumping = 8.00 hours/day
fan load = 0.0 W. quantity = 0.0
measuring system in a control room = 200.0 W.
measuring system is operated during night time = 12.00 hours
measuring system is operated during daytime = 12.00 hours
other loads = 0.0 Ah
battery efficiency = 0.85
line loss factor = 0.95
regulator efficiency = 0.85
inverter efficiency = 0.85
rectifier efficiency = 0.85
variability factor of climatic data = 0.90
mismatch of modules = 0.95
mean annual daily solar radiation at selected tilt angle = 4.482 kWh/m^2.
no. of modules connected in series in a panel = 15.00 modules
no. of cells per module = 36.0 cells
voltage at the maximum power point of a module = 18.00 VDC
current at the maximum power point of a module = 4.72 ADC
days of autonomy required for radio (night time)= 5.0 days

days of autonomy required for radio (daytime) = 0.0 days
days of autonomy required for lighting 8.0 W. (night time) = 5.0 days
days of autonomy required for lighting 18.0 W. (night time) = 5.0 days
days of autonomy required for lighting 36.0 W. (night time) = 5.0 days
days of autonomy required for street lighting = 5.0 days
days of autonomy required for TV (night time) = 5.0 days
days of autonomy required for TV (daytime) = 0.0 days
days of autonomy required for video (night time) = 5.0 days
days of autonomy required for video (daytime) = 0.0 days
days of autonomy required for fridge (night time) = 5.0 days
days of autonomy required for fridge (daytime) = 5.0 days
days of autonomy required for measuring system (night time) = 5.0 days
days of autonomy required for measuring system (daytime) = 5.0 days
days of autonomy required for pumping = 2.0 days
maximum permissible depth of discharge = 0.50
average battery voltage discharge = 240.0 VDC
ampere-hours rated of each battery = 200.0 Ah 12.0 V
power factor = 0.85
output voltage of inverter to load = 220.0 VAC

4.4.1.2 The Results of Designing a Centralised PV Mini-Grid System

: Design Location :
site : Udon-Thani Thailand
latitude : 17.38 Degrees North
annual average daily solar radiation at latitude angle: 4.482 kWh/m^2/day

: Location Size :
no. of households in the village 100.0 households
total actual daily load demand 39.67 kWh/day

: System Voltage :
nominal system voltage (DC side) 240.0 VDC
output voltage of inverter at load (AC side) 220.0 VAC

: PV system (array size) :
no. of cells per module 36.0 cells
no. of modules connected in series in a panel 15.0 modules
total no. of panels 16.0 panels
total no. of modules 240.0 modules
total no. of cells 8640.0 cells
peak current (cells can generate) 75.52 ADC
peak voltage (cells can generate) 270.0 VDC
peak power of system (cell can generate) 20.39 kW(peak)
cells area 130.71 m^2
array area 151.11 m^2

: PV System (storage battery capacity) :
total energy demand during daytime 10.35 kWh/day
total energy demand during night time 29.32 kWh/day
total no. of Ah which is designed 1600.00 Ah
Ah rated of each battery 200.0 Ah 12.0 V
no. of batteries connected in series in a string 20.0
no. of rows connected in parallel 8.0
total no. of batteries used 160.0
daily depth of discharge 11.12 %

: Size of Inverter :

inverter size that is designed 16.0 kW
ratio of power limiting function (array/inverter) : 1.27
power factor 0.85
output current of inverter (full load on AC side) 85.56 A
system voltage of load (AC side) 220.0 VAC 1.0 phase

: Size of back-up generator :
back-up generator designed 15.5 kW
system voltage of generator 220.0 VAC 1.0 phase
power factor of generator estimated 0.85
rectifier sized 9.50 kW

: System Parameters :
mismatch of cells 0.95
battery efficiency 0.85
regulator efficiency 0.85
inverter efficiency 0.85
variability factor of climatic data 0.90
line loss factor 0.95
maximum permissible depth of discharge 0.50

4.4.2 Analytical Evaluation of the System Performance with Daily State-of-Charge of Battery in the Case of a Centralised Mini-Grid System.

The main point considered in this topic is daily state-of-charge (SOC) of the battery to show the best relationship between the size of the PV array and the battery capacity. Indeed, the inputs of the simulation programme consist of the following main factors, the PV array size and battery capacity, load profiles, system parameters, I-V characteristics of a solar module as well as the climatic data.

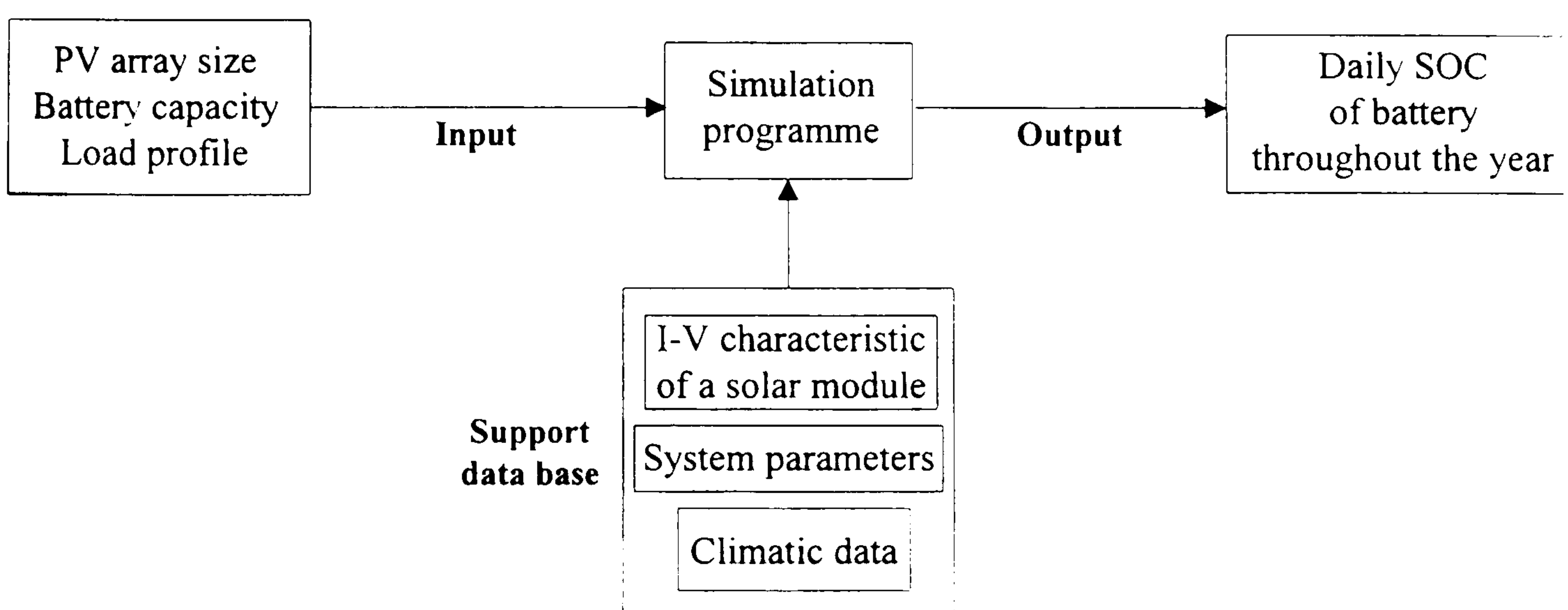


Figure 4.3 Block diagram of a computer programme for prediction of the best matching between the PV array size and battery capacity

The climatic data at Udon Thani province of Thailand is used for design in a sample village. As previously analysed, the optimum tilt angle for fixed installation (without tracking system) of a PV array in Thailand is approximately latitude angle. Hence, daily solar irradiation on a tilted surface at the latitude angle for Udon Thani province needs to be used as an input of this source programme.

4.4.2.1 The Input Data

Based on the block diagram above, the following data are the input into a computer programme: (i) I-V characteristics of a solar module # BP585, (ii) annual mean daily solar irradiation on a tilted surface at the latitude angle for Udon Thani province, (iii) system parameters from the previous design (iv) daily and night time loads, (v) mean hours of sunshine at Udon Thani Province. Moreover, the maximum temperature of cells during operation is also used as an input. It can be found from the following equation:

$$T_M = T_{amb} + (NOCT - 20) \tag{4.5}$$

where

T_M = maximum cell operating temperature (°C)

T_{amb} = maximum ambient temperature at design location (°C)

NOCT = normal operating cell temperature (°C)

(The NOCT is measured by comparing the temperature of the test module at thermal equilibrium with that of a reference module of known NOCT, when positioned side by side in still air in front of a stable (± 1%) and uniform (±3%) simulator. The irradiation in the test plan is previously adjusted so that the reference module achieves a final temperature of (ambient air temperature, 20° C) above its NOCT. The final temperature of the test module is measured under these conditions and its NOCT is then obtained by subtracting (ambient air temperature, 20°C))[17]

The maximum ambient temperature (T_{amb}) in Thailand is approximately 35°C [17]. From equation 4.5, T_M is equal to 56°C (while NOCT = 41°C) that is used as an input to source programme to calculate the SOC of the battery. A flow diagram can be seen in appendix B.

4.4.2.2 The Results of the Computer Programme

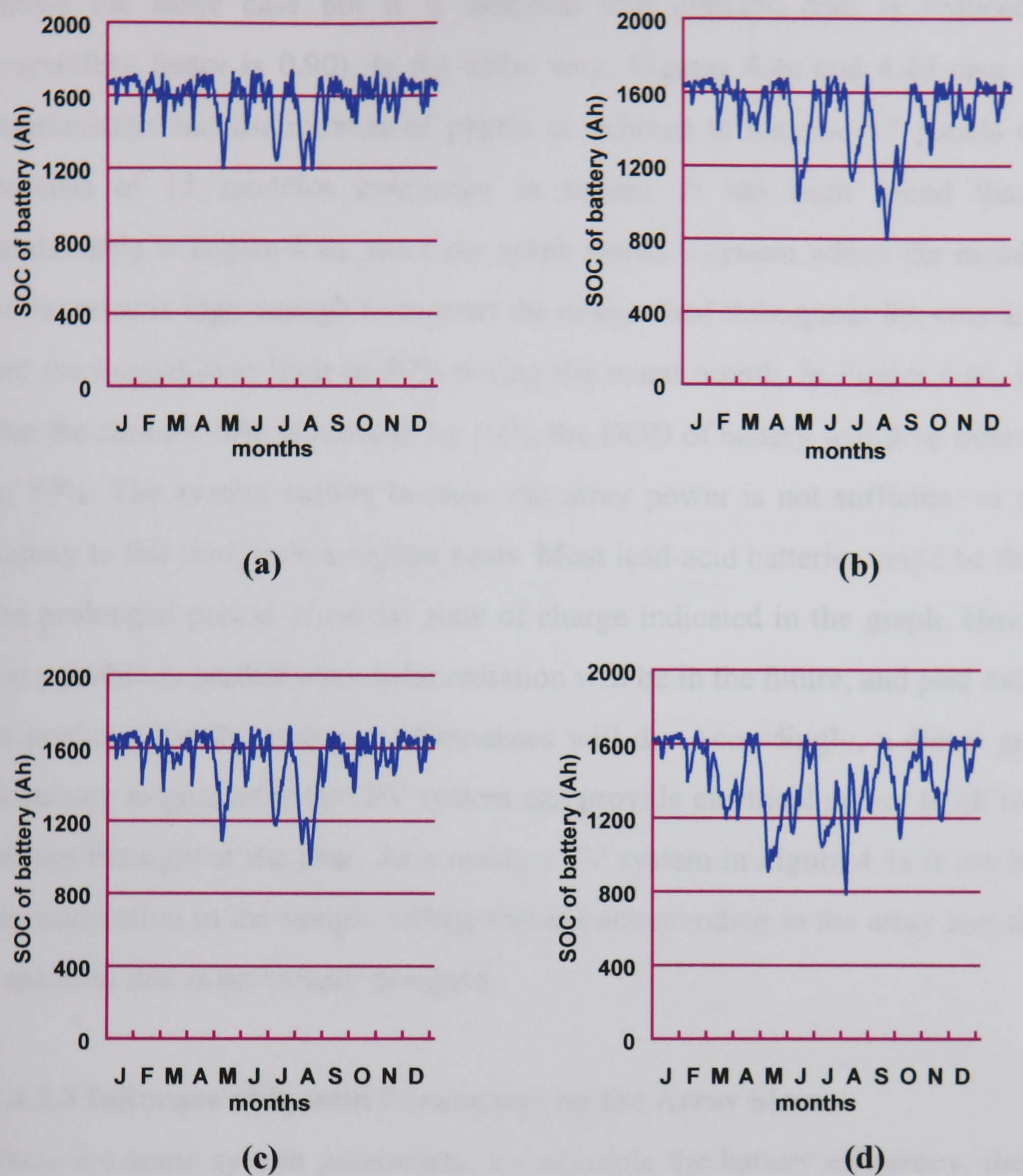


Figure 4.4 Daily SOC of batteries based on climatic data at the sample village

a) for a 1600 Ah 240 VDC (16 panels)
b) in the case of climatic data reduced by 10%
c) for a 1600 Ah 240 VDC (15 panels)
d) in the case of climatic data reduced by 10%

The deep cycles occur when charging during the day is not enough to replace the amount of charge used by the appliances. Therefore the SOC after each daily cycle is reduced slightly and this builds up to a deep cycle over a period of several days. When the weather improves or the days lengthen, there is extra charging and the state of charge after each daily cycle gets higher. As can be seen from Figure 4.4 (a through d), these figures show the relationship between PV array size and storage battery capacity in different conditions. In fact, Figure 4.4a shows their relationship for a system with PV array size of 16 panels and a 1600 Ah battery capacity. Figure 4.4b shows the same case but it is assumed that climatic data is reduced by 10% (variability factor is 0.90). In the same way, Figures 4.4c and 4.4d also show their relationships but the number of panels is reduced to become 15 panels (one panel consists of 15 modules connected in series). It has been found that the best relationship is Figure 4.4a, since the graph shows a system where the installed power of the array is high enough to support the design load throughout the year and DOD is not discharged over limit of 50% during the worst month. In Figure 4.4c, in the case that the climatic data is reduced by 10%, the DOD of battery will drop below the limit of 50%. The system suffers because the array power is not sufficient to restore the battery to full charge on a regular basis. Most lead-acid batteries could be damaged by the prolonged period of partial state of charge indicated in the graph. However, it is not possible to predict what solar radiation will be in the future, and past data are used to predict what the system performances will do. Accordingly, a diesel generator is necessary to guarantee that PV system can provide electrical power to all loads in the village throughout the year. As a result, a PV system in Figure 4.4a is the best choice for installation in the sample village that is corresponding to the array size and battery capacities that is previously designed.

4.4.2.3 Influence of System Parameters on the Array Sizes

There are some system parameters, for example the battery efficiency, the regulator efficiency, the inverter efficiency etc., will directly affect the number of modules in an array size. It is supposed that these parameters are a constant called "K". Figure 4.5 shows the influence of K on the number of modules based on solar radiation at Udon Thani province of Thailand.

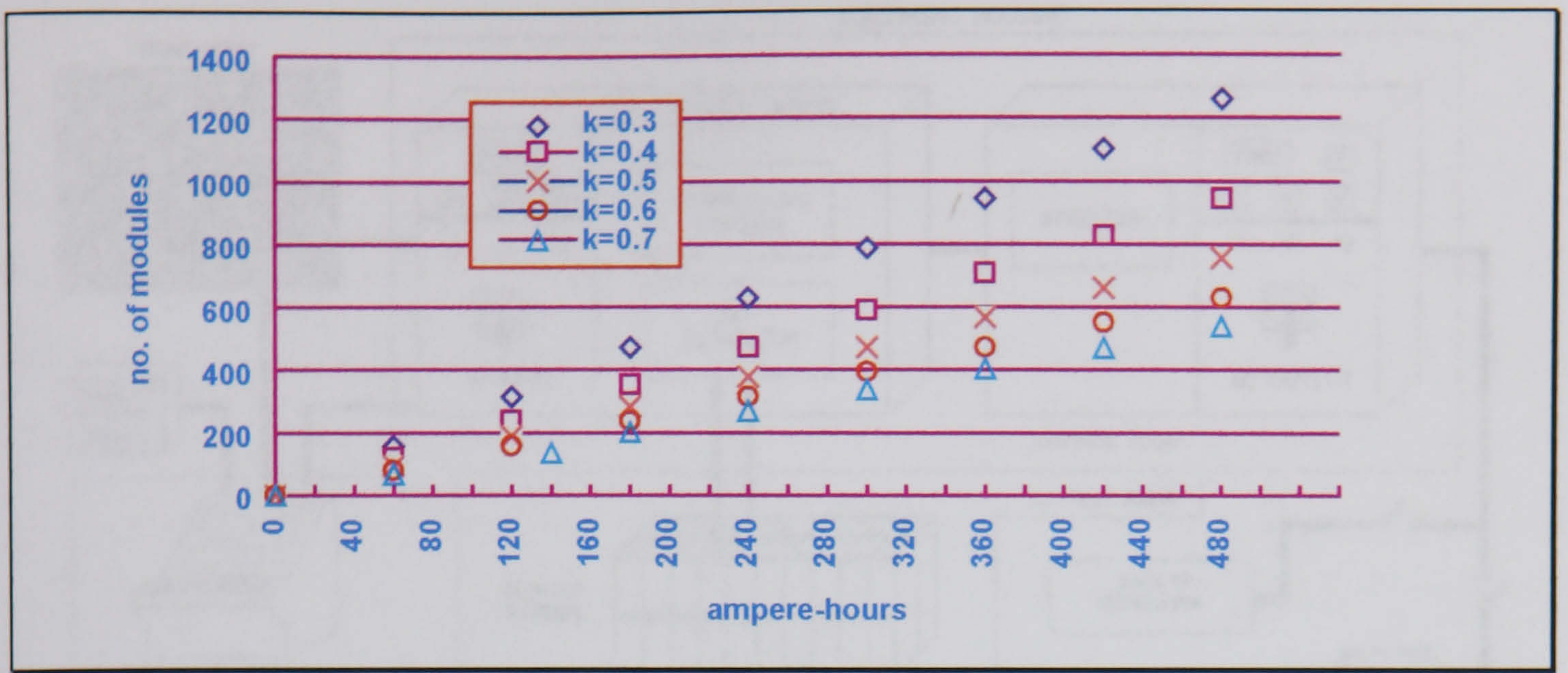


Figure 4.5 Influence of a constant K on the number of modules based on solar radiation at the sample village (Udon Thani of Thailand)

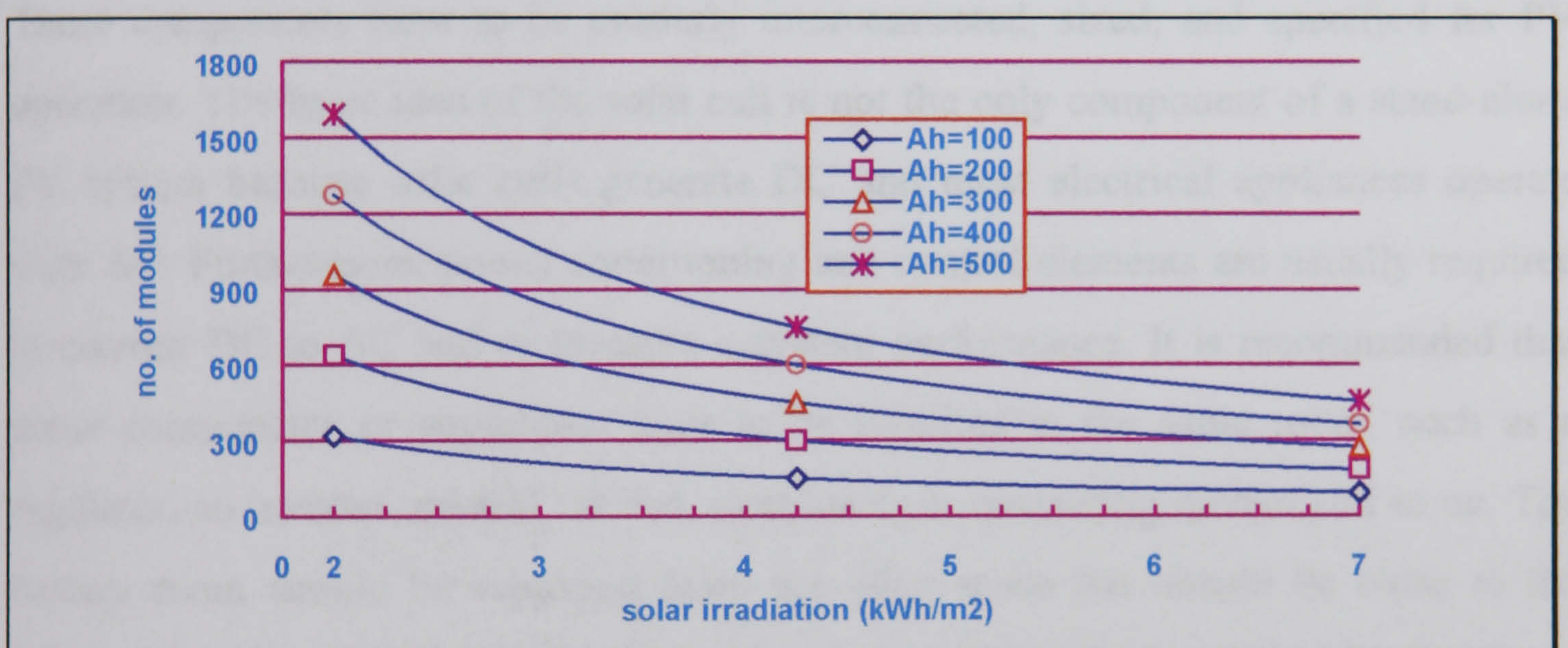


Figure 4.6 Influence of daily load demand on the number of modules (K=0.55)

4.5 Conceptual Design of System Components of a PV Mini-Grid System

Most PV panels are used to charge storage batteries, that can provide power to the appliances at any time. The main parts of the stand-alone PV system are the PV array and battery bank. They can not completely work without other necessary components, such as blocking diodes, bypass diodes, DC regulator, monitoring or measuring systems and an inverter. The block diagram is shown in Figure 4.7. A stand-alone PV system used for rural electrification consists of various subsystems or system components.

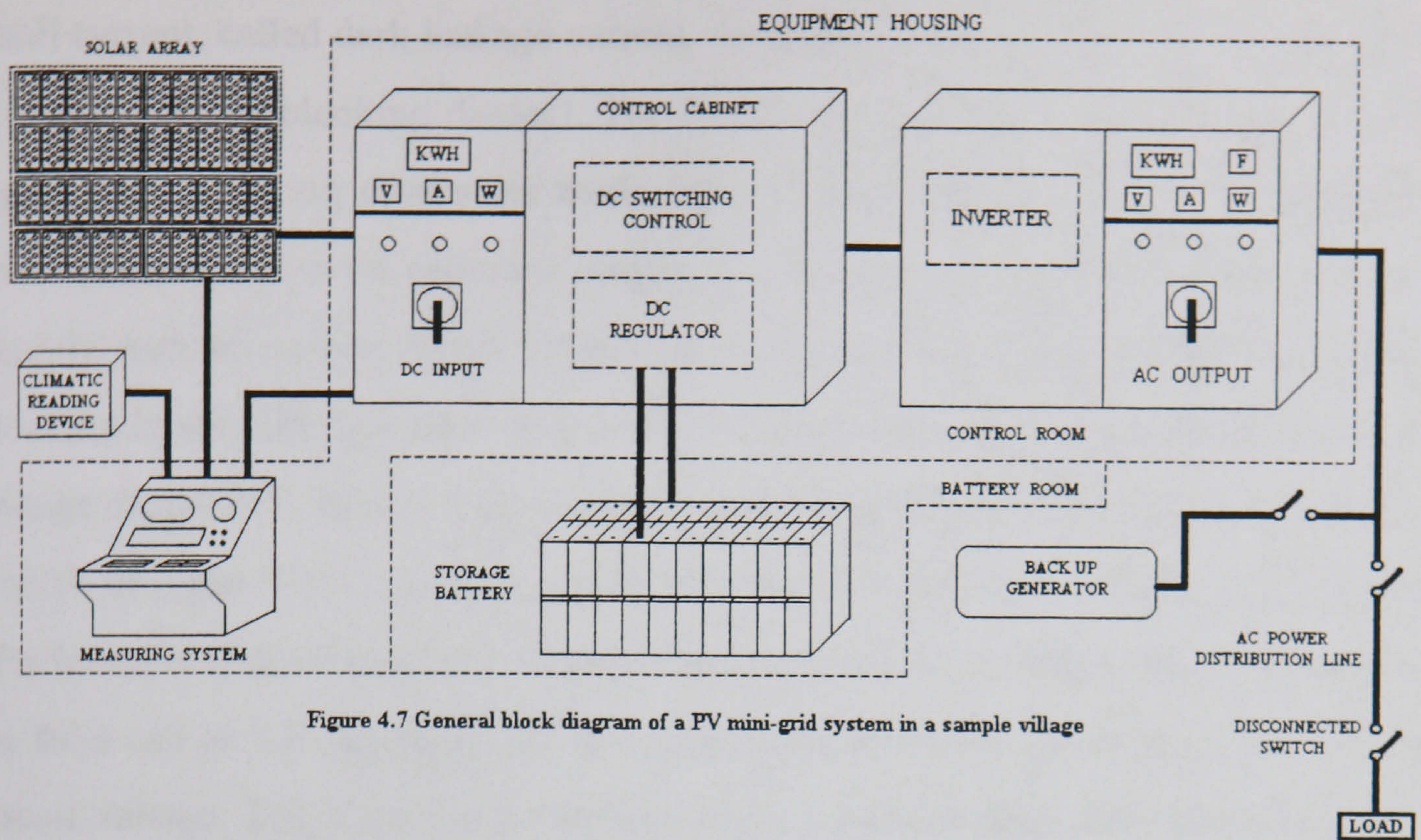


Figure 4.7 General block diagram of a PV mini-grid system in a sample village

These components have to be properly interconnected, sized, and specified for PV operation. The basic idea of the solar cell is not the only component of a stand-alone PV system because solar cells generate DC and most electrical appliances operate with AC. Furthermore, power conditioning and control elements are usually required to convert DC to AC and to measure a system performance. It is recommended that some components or equipment have to be installed in the same room, such as a regulator, an inverter, control cabinet, monitoring or measuring system and so on. The battery room should be separated from the other room but should be close to the power conditioner to avoid power losses due to the length of wires. The details of characteristic of these components can be described as follows:

4.5.1 Diode Applications

Application of diodes can be used in stand-alone PV systems, especially solar cells arraying. There are two major applications of diodes in a particular PV system, namely they are used as the blocking and shunt (bypass) that can be addressed as follows:

4.5.1.1 Blocking Diodes

Blocking diodes are permanently connected between the electrical string of solar modules and a power bus. They will conduct electric current from illuminated cells or modules to a DC bus through the solar string. In practice, the modules allow a very small current, called dark leakage current, from the battery to flow back through them at night (without blocking diodes). The dark current can be prevented by a blocking diode. Most blocking diodes are made from silicon, and have a typical voltage drop about 0.7 V. Two extra cells are needed to compensated for this voltage drop, so a module with thirty-two single crystal silicon cells is self regulating with a silicon blocking diode. The Schottky type of silicon diode and germanium diode both have a voltage drop 0.3 V, hence, a module with thirty-one cells is self regulating when used with these types. The amount of current that can be drained by a shaded array or string of solar cells without blocking diodes depends on the bus voltage and the steepness of the solar cell or I-V characteristic curves between the power maximum point and open circuit voltage. The blocking diodes can cause a voltage drop that subtracts from the solar cell output voltage and causes an energy loss when the solar cells produce some energies. Furthermore, the blocking diodes are able to prevent series or even catastrophic power subsystem failure by short circuit, they are properly placed. There are four possible locations for blocking diode near module array that can be illustrated in Figure 4.8. The impact of diode and wire faults on the power subsystem capability of a simple and hypothetical system is shown in Table 4.5.

Table 4.5 Illustration of impact on power subsystem performance when a single point failure on the array/structure occurs. (Hypothetical solar cell array consists of four strings with redundancy) [25]

Subsystem power loss (percent)				
Configuration*	Failure of one diode		Failure of one wire	
	Short	Open	Short to ground	Open
A	~ 0	25	100	25
B	~ 0	100	100	100
C	~ 0	25	25	25
D	~ 0	50	50	50

* Based on Figure 4.48

For a failure mode, an analysis of effect similar to that are described in the table above can be performed for each array design to determine the optimum location of the blocking diodes. Typical isolation diodes are conventional, high reliability rectifier diodes with suitable current ratings. They have been developed to have the physical property of solar cells and the electrical property of conventional rectifier diodes [25]. However, the blocking diodes selected correspond mainly to the criteria as follows:

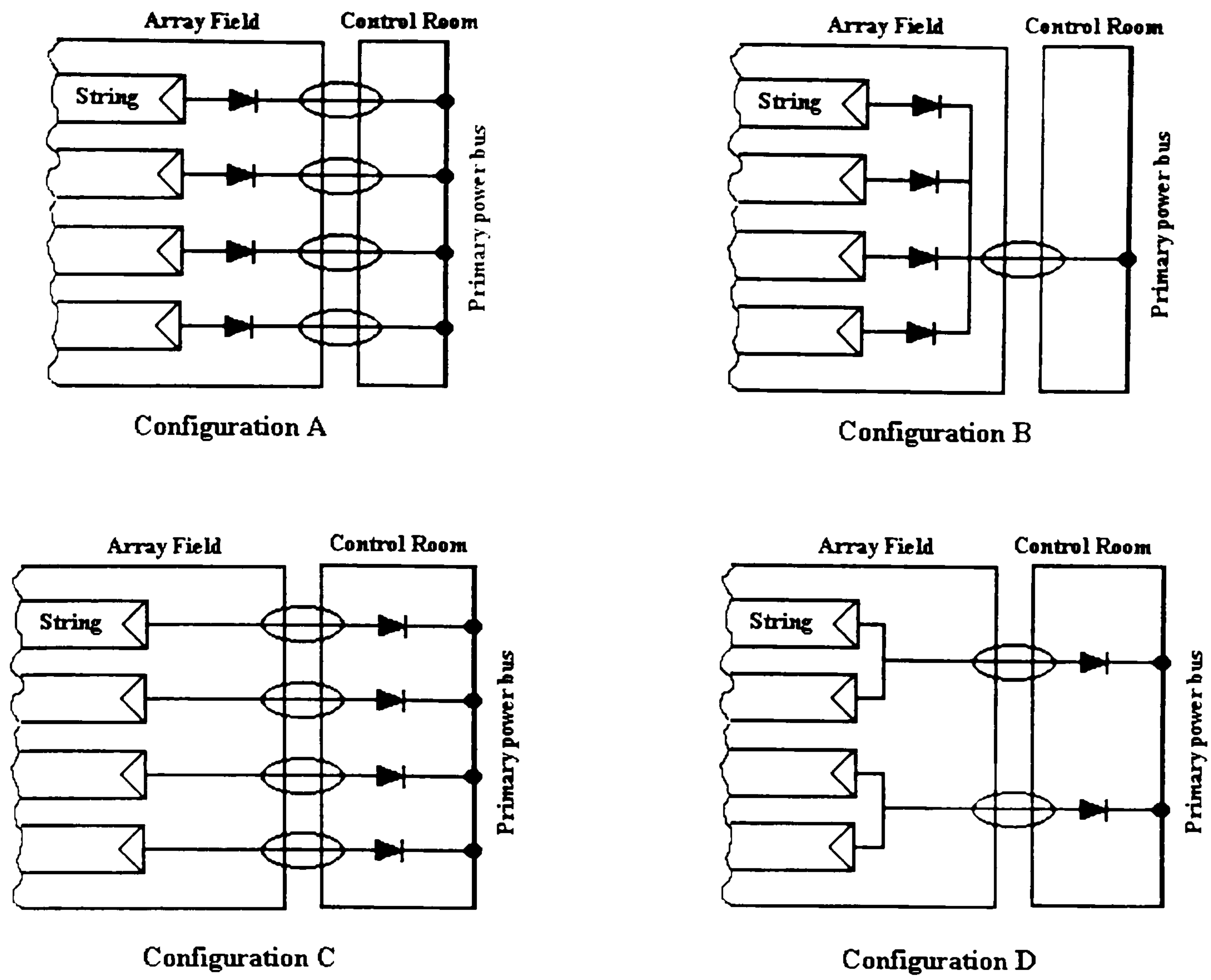


Figure 4.8 Some possible blocking diode locations.

- Forward voltage drop at the nominal current level and at the actual diode operating temperature is as low as possible (this current level is an average or peak current at end of life).
- Sufficient rating of peak inverse voltage is based on highest bus voltage with superimposed transient voltage spikes.
- Capability to withstand temperature cycling throughout mission life without mechanical or electrical failure.

Nevertheless, some modules already have the blocking diodes in their junction box which simplifies the connections. The diode in the box may be a bypass one that serves a different purpose. The identity of a diode should be checked with the instructional booklet that comes together with the module to see whether a separate blocking diode is needed or not.

4.5.1.2 Bypass or Shunt Diode

It is connected in parallel with the solar cells or a module such that when the solar cells are illuminated the bypass diode is reversely biased. The problem can occur as the hot spot heating when a few cells in one module (or a few modules in a string) are shaded. In this circumstances, the bypass diodes will be automatically forward biased and permit power to flow from the rest of the illuminated cell (module) in the string to the power bus, so the shaded cells' damage can be prevented by the connection of the bypass diode. For the problem of a module being partly shaded while the rest of the module in a string is in full sunshine. Manufacturers mention concerning about this problem that polycrystalline silicon cells are resistant to hot spot damage under condition of reverse bias. On partial shading of some modules in a series/parallel string, the total power of PV array can be decreased by this event. Solar modules (cells) in an array that are subject to shading may become permanently damaged from high reverse voltages and power dissipation, so that the modules are permanently short-circuited will probably occur. As a result, to partly overcome the problems of mismatch, bypass diodes are often connected across sub-strings of cells. When a mismatch condition exists, the bypass diode may become forward biased, thus preventing current limiting. This reduces power loss due to mismatch and limits the maximum power dissipation in any cell to the power generated by the bypass cells, thus avoiding hot spot heating. To minimize both power loss and hot spot heating, arrays should ideally include one bypass diode across each cell [26]. However, this approach is usually too expensive and requires many additional connections. To overcome these limitations, an integral bypass diode may be fabricated into the cell structure. This approach is potentially cheaper and requires no additional inter-cell connections [26].

As previously designed in this project, the centralised PV mini-grid system for the sample village at Udon Thani province of Thailand consists of 240 modules. Accordingly, the number of modules connected in a series string is 15 and total number of strings is 16. The connecting of blocking and bypass diodes to protect some crucial failure of modules can be illustrated in Figure 4.9. The optimum location to install the blocking diodes is to place them in the position C based on analysis in Figure 4.48 and Table 4.5 [25].

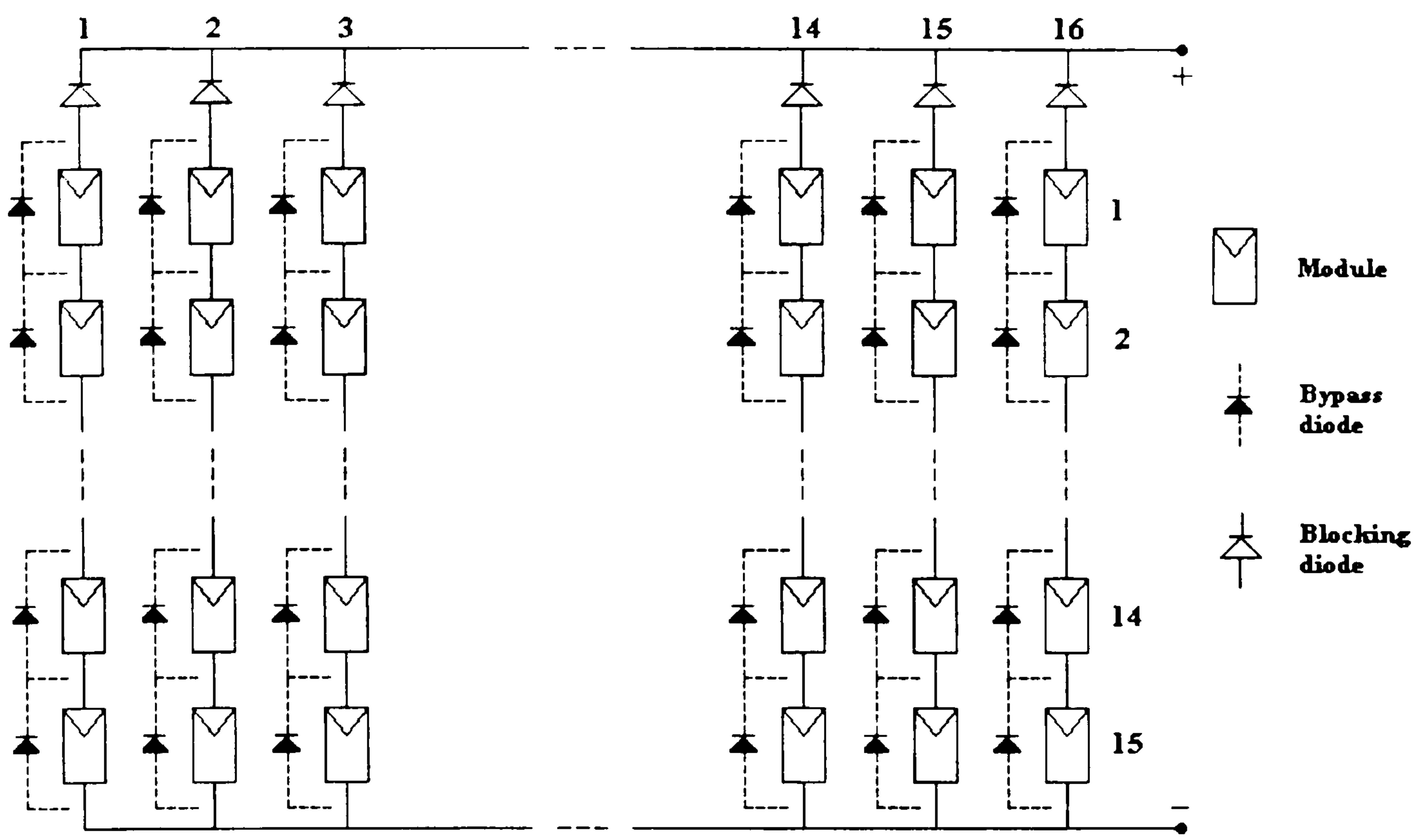


Figure 4.9 Blocking and bypass diode connected in a PV array

4.5.2 Charge Regulators

A charge regulator is used to manage energy flow to the PV array, storage battery and load. It also prevents battery damage from overcharge and deep discharge. The charge regulator is modeled as follows: electrical energy from the array is used to meet the load before any excess is stored in the batteries. If the load cannot be met by the array alone, the difference is requested from the batteries. When the battery state of charge drops to the minimum value permitted, the regulator will be disconnected from the load. The electronic device designed to protect the battery against deep discharge and overcharge condition is known as the battery charge regulator or battery voltage regulator. Basically, it will disconnect the load from the battery when the state of charge (SOC) of the battery drops below a specified value, so that deep discharge is prevented. When the SOC exceeds a certain value, the PV array is disconnected from the battery to avoid overcharging (and consequent gas formation) of the battery. However, disconnection of the PV array while the battery is fully charged results in a loss of part of the available array power. Typically, there are two main functions of the regulator. Firstly, battery top-of-charge regulation to ensure that batteries are not overcharged, but that they also receive sufficient charge. Thus some gassing should be possible to avoid stratification of the battery electrolyte and to allow batteries to reach as close to full charge as possible, however, excessive gassing should be avoided. Secondly, load disconnection is to regulate excessive discharge of battery capacity. The regulator may also provide an indication of the status of the system, whether the battery is being charged or is fully charged. Regulator must be sized to handle the maximum current produced by the PV array.

4.5.2.1 Stand-Alone PV System Regulator

The energy flow in a simple PV power system is composed of solar modules, storage batteries and loads that can be normally described as follows. The floating operating condition occurs when the battery voltage fluctuates between maximum and minimum voltage thresholds corresponding respectively to the level SOC of battery. The overcharge and deep discharge conditions occur when the battery voltage reaches some critical value. In this case, the regulation that will be later performed by the regulator consists of collecting information on the state of the system (battery voltage - V_B), minimum SOC (V_{min}) and maximum SOC (V_{max}). The general principle of battery charge regulator is that the battery is usually used in a PV system as a buffer between the PV array and the load as shown in Figure 4.10, the switches S_1 and S_2 are made active [27].

(i) If SOC of the battery is below a critical value (denoted by SOC_{min}) the switch S_2 is opened to avoid over discharging of the battery. As a consequence, the load is not supplied with power and the battery charges through the PV array. When the battery charged by PV array reaches a given level SOC_1 that is greater than SOC_{min} (see Figure 4.10b.). The switch S_2 reconnects the load. The difference value between SOC_1 and SOC_{min} is known as the hysteresis (H_1).

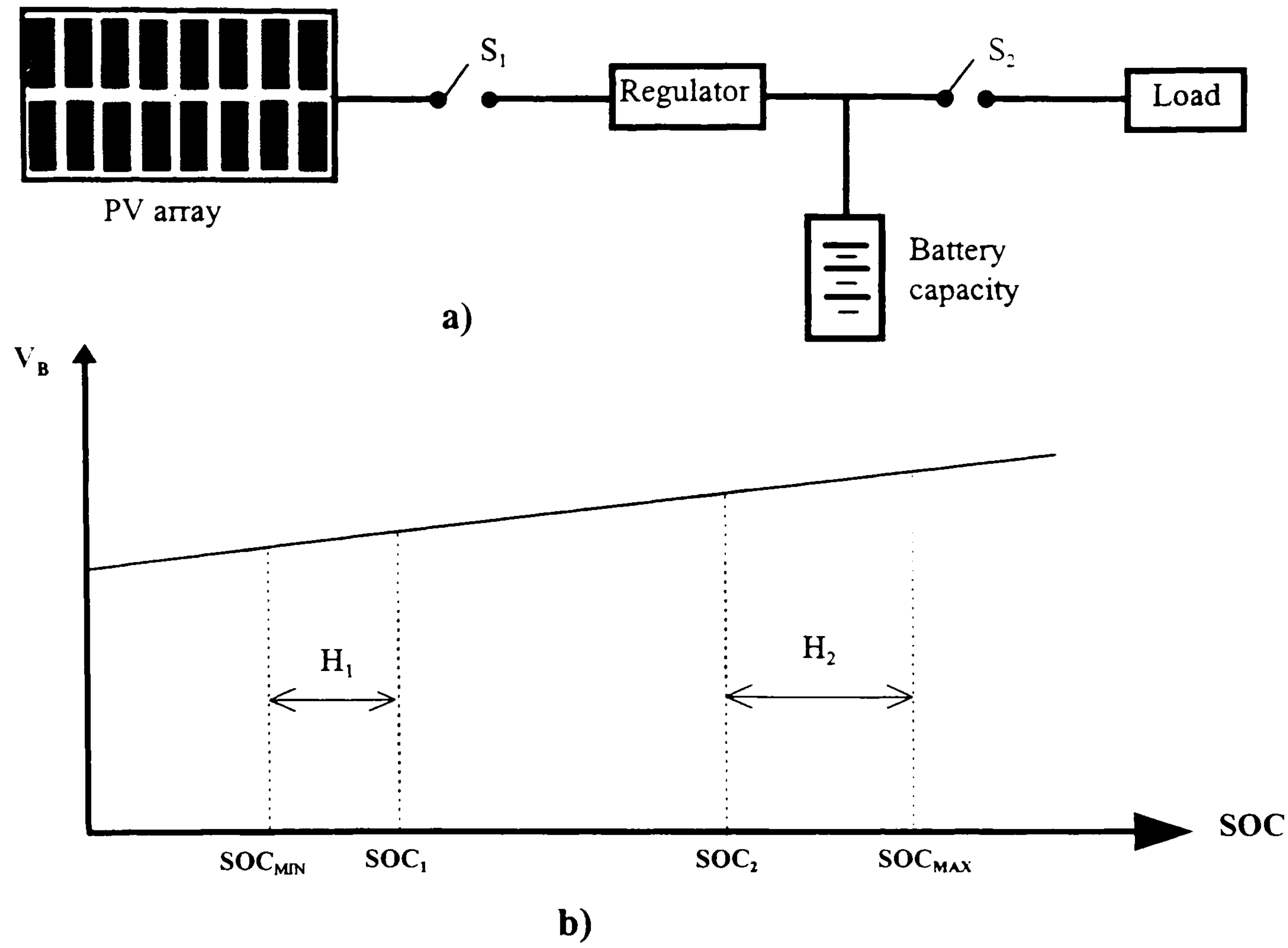


Figure 4.10 a) Basic connection scheme for a PV system with regulation.
b) Variation of battery voltage V_B against state of charge (SOC).

(ii) If the state of charge reaches SOC_{max}, the switch S_1 disconnects the PV array and the load will be supplied by the battery. When the state of charge of the battery becomes SOC_2 that is (smaller than SOC_{max}) the switch S_1 reconnects the PV array to the battery. The difference value between SOC_2 and SOC_{max} is known as hysteresis (H_2). Normally, the values of SOC_{min} and SOC_{max} are specified by the battery manufacturer, however they can be adjusted by the battery voltage regulator according to the battery types that is used in a PV system. SOC_1 and SOC_2 are controlled by the circuit of battery voltage regulator according to the requirement of hysteresis. In the case that the hysteresis H_1 is increased, the power supply to load will be interrupted for longer periods, and the available power to the load is less. On the other hand, if H_1 is reduced the switch S_2 will be connected (and disconnected) frequently and the lifetime of the switch becomes shorter. For the switch S_1, if the value of H_2 is larger, the battery cannot be charged by the PV array for longer periods. To minimise this power loss H_2 has to be reduced, but again the lifetime of switch S_1 is shortened. Moreover, the PV system must economically design and the battery capacity is limited during high radiation levels the battery may be disconnected from the array when it is fully charged. It is impossible to avoid power loss due to the PV array disconnection unless the storage battery bank is oversized. An oversized storage battery means higher PV system cost.

4.5.2.2 Principle of Self-Regulation

In a small PV system, the connection of the battery with a solar module via a blocking diode provides the simplest solution. This configuration relies on a correct choice of the operating point of a solar module. Matching will take place between the battery voltage under the minimum SOC and the voltage at the full charge, allowing for a voltage drop across the blocking diode of approximately 0.7 V. If the array operating voltage is set at the upper end of this voltage range, a slight increase in the battery voltage then sharply reduces the charging current from the PV generator and prevents battery overcharging. The I-V curves are drawn for the cell temperatures expected in a mild climate with an air temperature of about 20°C (70°F). At full sun of 1000 W/m^2, the cells are heated by the sun, so the I-V curve for 50°C is shown in Figure 4.11b.

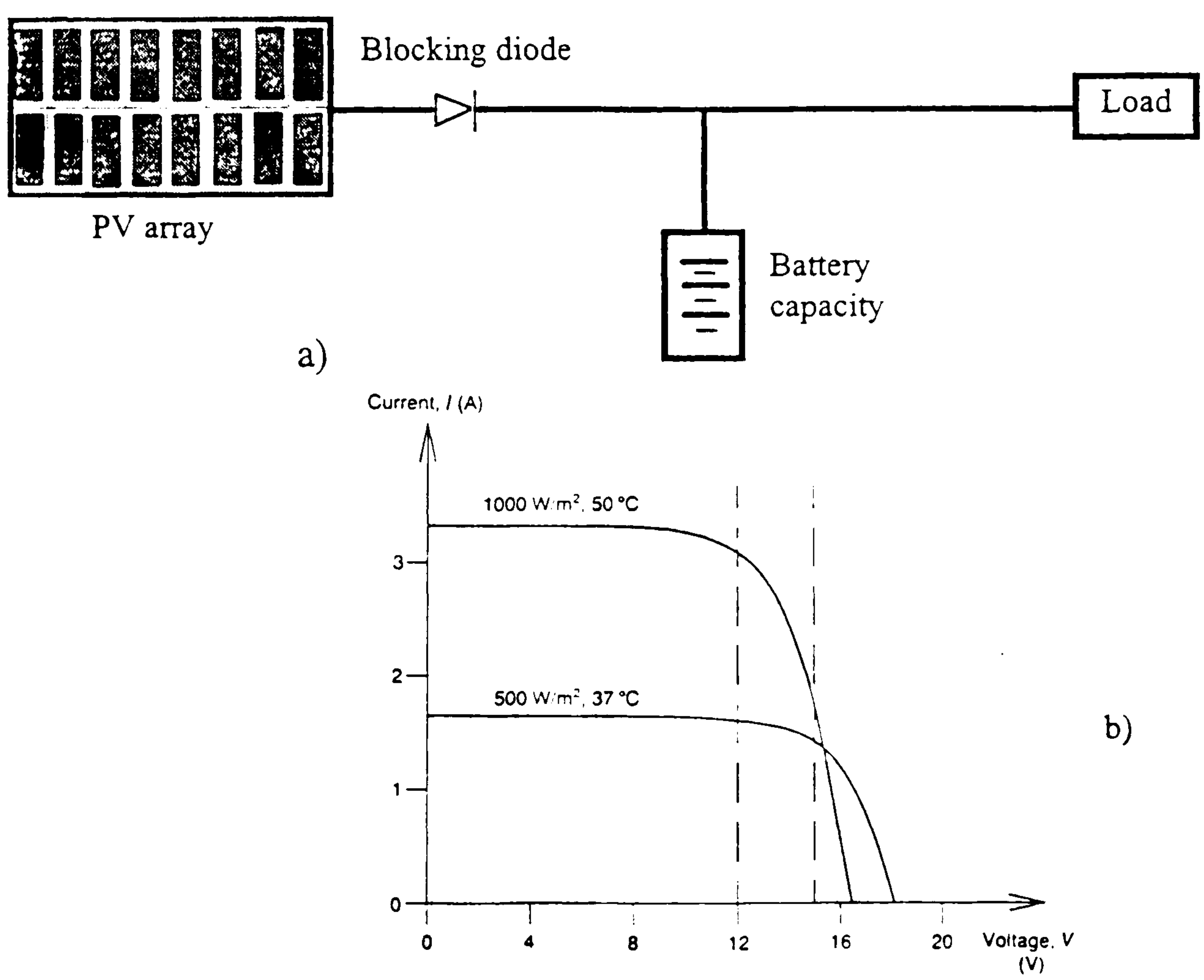


Figure 4.11 a) Self regulation
b) I-V curves for a module with thirty single crystal silicon cells that is self-regulation when charging a 12 V lead acid battery

At a lower solar irradiance of 500 W/m^2, the temperature difference between the cells and the surrounding air is less. The vertical broken line for 12 volts crosses both I-V curves at high current. The vertical line for 15 volts crosses both I-V curves at low current. Therefore the module automatically supplies a low current while the battery is fully charged. When the modules are called "self-regulating", it does not mean that they contain some sort of electronic regulating units inside. All it means is that the electrical characteristic of the module allows it to be directly connected to a battery and a separate regulating unit is not needed. These characteristics are summarized by the figure above. A self-regulating system may be least effective way of extracting energy from the PV array because the battery voltage requirement places specific constraints on the array operating voltage and current, forcing it to operate most of the time away from its maximum power point. As an example, a 12 V of lead acid battery that has a charge voltage that ranges from 12.8 V at 60% of SOC to 14.4 volts at fully charged [17]. The voltage operating point of the array that would transfer maximum power from the array is 14.4 V plus the voltage drop across the blocking diode (typically 0.7V) or a total of 15.1 V. The PV modules must be connected to produced 15.1 V. When the battery voltage equals the voltage of the array minus the diode voltage that occurs when the battery is fully charged, current stops flowing into the battery from the array. However, a disadvantage of a self-regulating module is that the last period of charging is at a very low current and needs many hours of sunshine. By using a module with more than thirty-two cells, the maximum charging current is maintained at 16 V and the battery reaches full charge in the shortest time and the charging current is also low in cloudy weather.

4.5.2.3 Shunt (parallel) Regulation

The regulator will be connected in parallel with the PV generator to dissipate any excess energy through a resistor and power components. The PV array connected to the battery behaves as a current generator. The current I_L is quasi proportional to solar irradiance. For a given irradiance level, I_L is a constant.

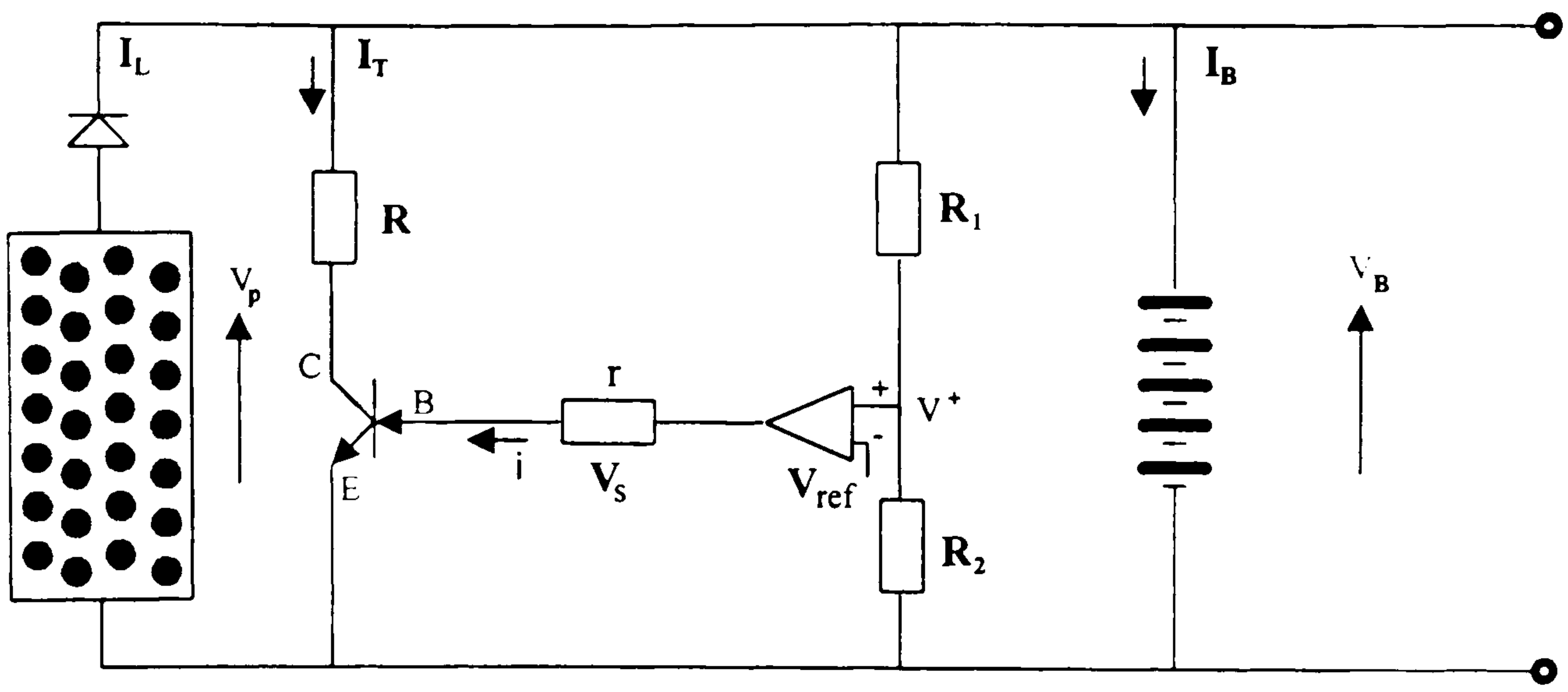


Figure 4.12 A simple design of a shunt regulator

Generally, switching regulators limit the voltage by disconnecting the solar array in steps or increments. For the shunt regulator in the figure above, if there is no regulation, the voltage V_B of the battery is less than the limitation voltage (denoted by V_{lim}) corresponding to the maximum SOC. In this case $V^+ > V_{ref}$ and $V_S = 0$, $i = 0$, because the transistor is off (i.e. $I_T = 0$). The shunt regulator does not interfere, as no component is in series with the power circuit of the PV generator, no voltage drop occurs and current is entirely used for changing the battery ($I_L = I_B$). It is assumed that $V_B > V_{lim}$, in this case, $V_S > 0$ and $i > 0$. Thus, the transistor can conduct because of a current flowing through resistor (R) and it means $I_T > 0$, so that $I_L = I_T + I_B$. An equilibrium is achieved when the current I_B is just sufficient to maintain the battery at the limitation voltage, then $V_B = V_{lim}$ and $V^+ = V_{ref}$. Some advantages of the shunt regulator are as follows:

- There is no voltage drop in the charging units.
- A failure in the regulators would not interrupt battery charging.
- The power consumption of the regulator is negligible during the no regulation period. On the other hand, the transistor should be able to dissipate one quarter of the total power and the resistance should be able to dissipate the total power when the transistor is in saturation.

In small applications (up to 100 W) a shunt regulator can be used to dissipate the unwanted power from the generator. A common implementation is to use a transistor in parallel with the PV array which is set to conduct and divert current from the battery at a certain threshold voltage value.

4.5.2.4 Series Regulation

In larger applications, it is advisable to disconnect the battery from the generator by means of a series regulator. This can be an electromechanical switch (i.e., a relay) or a solid state device, such as a bipolar transistor, MOSFET. The series regulator uses a transistor in series with the PV array. The transistor behaves like a variable resistance whose value is a function of SOC.

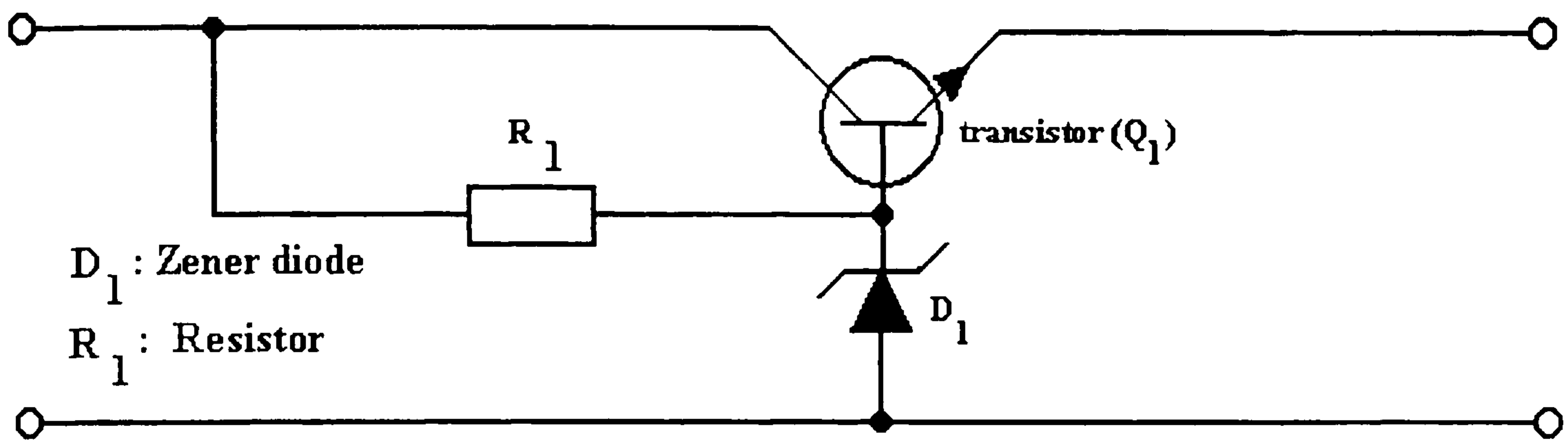


Figure 4.13 A simple design of a series regulator

Generally, other types of regulator fall into the incremental and/or switching regulator category. The characteristic curve of the PV array consists of a voltage region and a current region. A single silicon solar cell may be either open circuit or short circuit without damage to the cell. That is, on open circuit, the solar cell reverts to a voltage source, and when short circuited a current source. In both modes the power generated is zero. Theoretically, a solar array consists of a number of series cells having the same open circuit characteristics. It is a simple matter, therefore, to sense the battery voltage and open circuit the solar array when the voltage reaches the preset maximum. To prevent instability, some hysteresis is incorporated in the voltage sensing so that the solar array is switched back into the circuit at a lower voltage. In practice, a solid state switch is recommended because it is more convenient to use than an electromechanical switching device [28]. The transistor from the figure below is cut-off and power does not require to hold it in a saturated state.

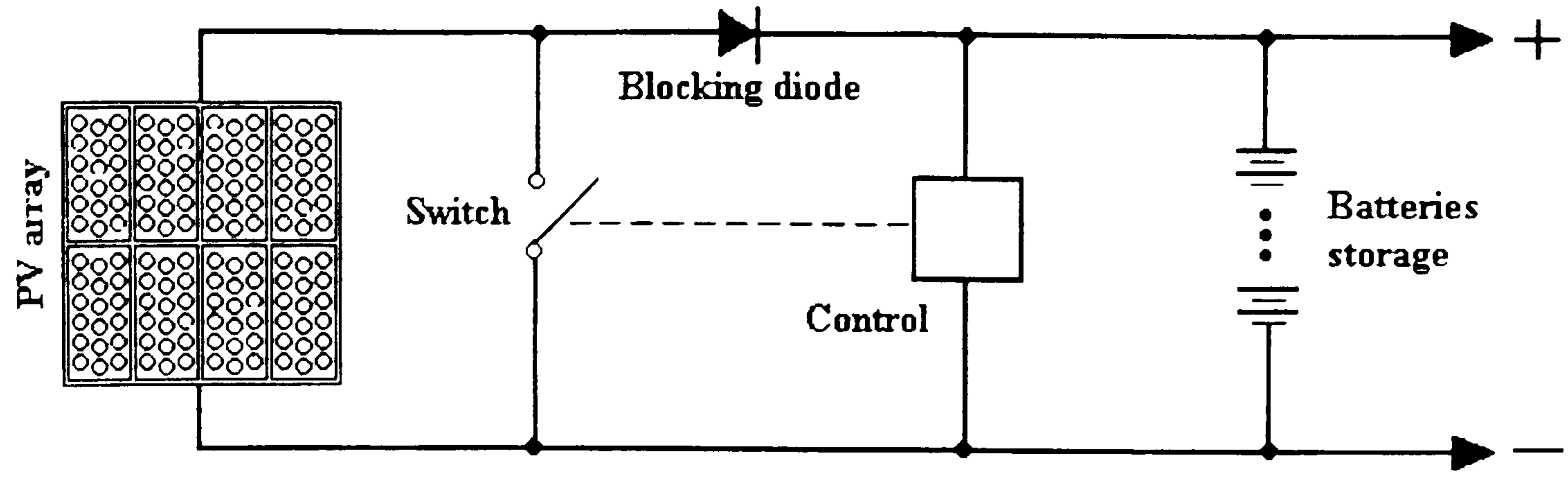


Figure 4.14 Regulating types: switching short circuit

To short-circuit a PV array as in Figure 4.14, it is convenient to use a power transistor as, under normal solar radiation conditions, the transistor is cut-off and power is not required to hold it in a saturated state. When the voltage level reaches the high cut-off level, the transistor is saturated and short circuits the PV array as shown in Figure 4.15.

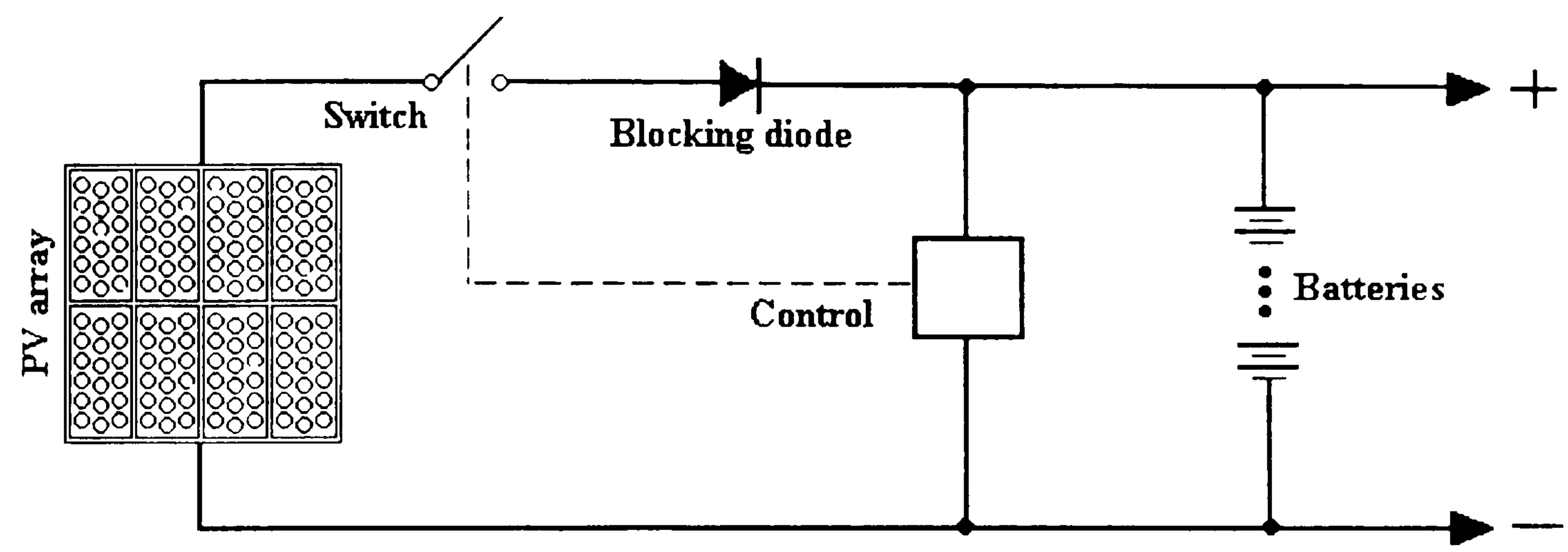


Figure 4.15 Regulator types: switching series

Under normal conditions, the transistor would have to be held in the saturated state and requiring a drive current. An additional circuit could be used to derive this current from the array output. Hence, the drive current passes through the series transistor to the load and battery. Other designs of the regulator depend on disconnecting the battery (not the array). When the batteries are fully charged, while the PV array is coupled to the load through a chopper circuit, thus no power is lost.

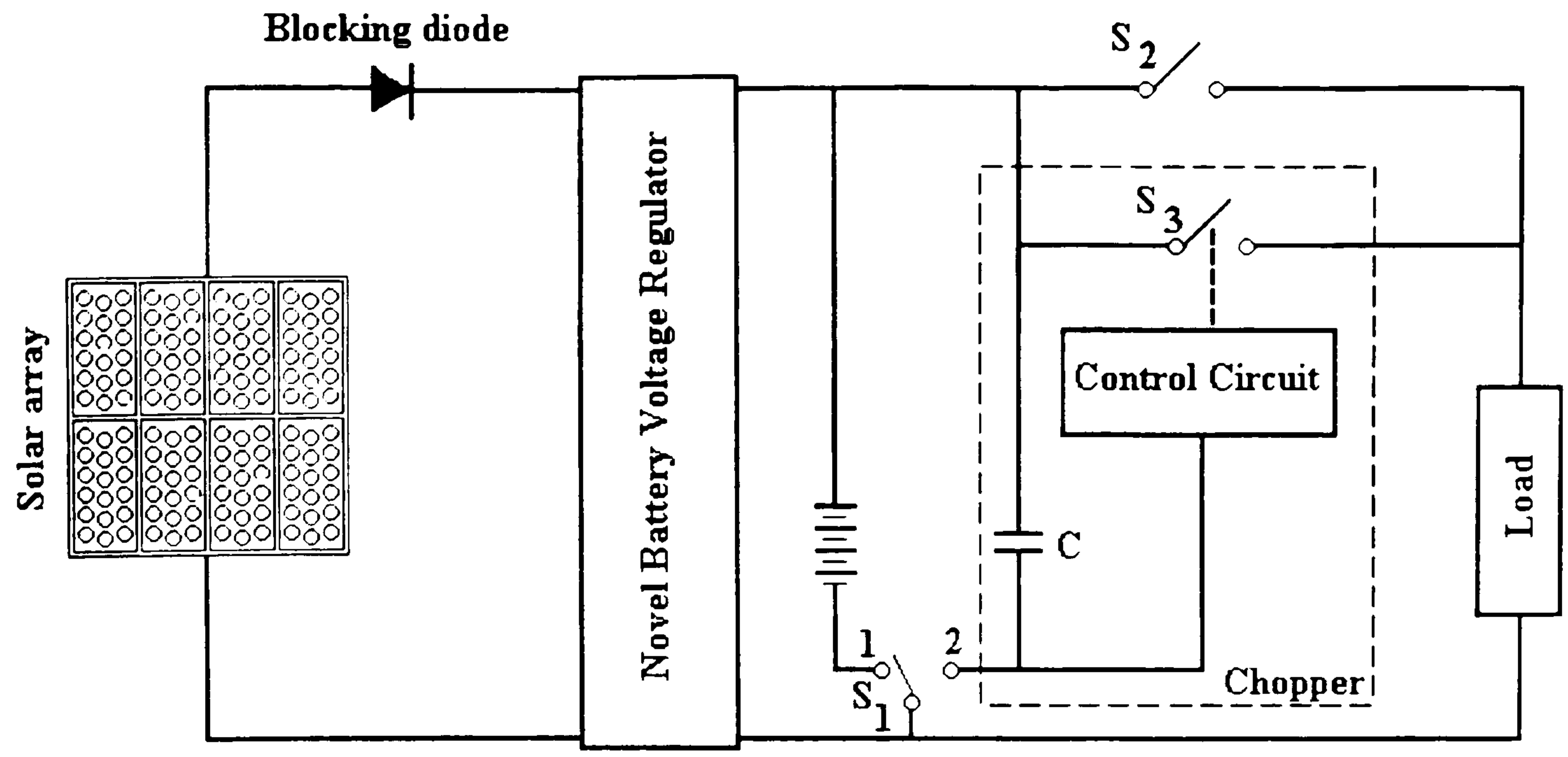


Figure 4.16 Schematic representation of the novel battery voltage regulator

As can be seen from the figure above, it functions as described below.

a) In the case that the SOC of battery is less than SOC_{min} the switch S_2 is opened, disconnecting the load and the battery that is charged by the PV array because of under these conditions the switch S_1 is in position 1.

b) If the SOC is between SOC_{min} and SOC_{max} , the switch S_1 is in position 1 and the battery will be charged by the PV array, while the switch S_2 is closed and the load is supplied by PV array.

c) If the SOC exceeds SOC_{max} , the switch S_2 remains closed and the switch S_1 is in position 2 so that the chopper circuit is connected to the load. The function of the chopper is matching between the load and PV array. It is preferable for the switches S_1 and S_2 to be mechanical relays with a long lifetime (mercury displacement relays), especially the load current is relatively large, to avoid any power losses in electronic switches. The method of switching in the regulator is not an important factor, so electronic switches can be avoide. The switches S_1 and S_2 are controlled by a Schmitt trigger circuit with reasonable hysteresis [27].

4.5.2.5 Voltage Set Points

The voltage set points will differ according to the battery types. Not all of these voltage set points will be applicable to all regulators. Preferably, charge and discharge curves should be available from battery suppliers to enable the system designer to choose appropriate points of voltage. When insufficient information is available, battery manufacturers should be required to generated the required curves. System designers should communicate their voltage set points from regulator manufactures, or purchased regulators should have clear instructions as to how to adjust voltage set points. Preventing the battery's excessive discharge to a very low SOC is probably the most important function of regulators. A battery that operates repeatedly below design depth of discharge level will fail prematurely. Regulators are designed to protect the battery from prolonged and unexpectedly low charge and unexpectedly high load demand by shedding loads at a specified voltage set point that gives the approximate permissible depth of discharge. Disconnection of the load and subsequent charging allows the battery voltage to rise until the load reconnect voltage set point is reached. This hysteresis window must be large enough to prevent many frequent load disconnects or connect switching. There are no limitations imposed about technology and methods used to implement charge regulation and no fixed requirements are made about additional functions and features that must be included. However, a charge controller may be installed as a stand-alone unit or it may be incorporated into a system. The following information and data will be supplied on request by a company.

- Choosing whether the controller is shunt or series type.
- Blocking diodes for preventing reverse current are incorporated.
- In the case of series regulators that the voltage drop across the regulator is over the allowable range of charging current.
- Adjustment range and these values are able to be changed by the user.

4.5.3 Inverters

Power conditioning equipment is used to change electrical power to be a more convenient form from the PV array. In direct current (DC) systems, most power conditioning is DC power conversion. DC/DC converters will increase or decrease DC voltage. DC power from battery can be changed to alternating current (AC) power using DC/AC converter is known as an inverter. The voltage of the DC source is normally 12,24,48 V, etc., while that at the inverter AC output is typically 110,220 V, etc. The output frequency is usually 50 or 60 H_Z [29]. It is needed when using appliances that only work from a main voltage AC supply. Although an inverter may be seen to be the best solution of running all the appliances, good quality inverters are expensive and difficult to obtain in many countries.

4.5.3.1 Types of Inverter

The types of inverter can be classified by the characteristic of their output voltage waveform. The shape of the output waveform is an important parameter. It can be broadly classified into three types as follows: (i) square wave (ii) modified sine wave (also called quasi sine) (iii) sinusoidal wave (very similar to electrical power from the grid). The output waveform depends on the conversion method and the filtering used on the output waveform to eliminate spikes and unwanted frequencies. Square wave inverters are relatively inexpensive, have efficiencies above 90%, high harmonic frequency content and little output voltage regulation they are suitable for the resistive loads. Modified sine wave inverters offer a better voltage regulation by varying the duration of the pulse width in their output efficiencies can reach 90%. They can be used to operate a wider variety of loads including lights, electronic equipment and motors. The nature of the non sinusoidal waveform interferes with the operation of less sophisticated appliances. In addition, it can interfere with some televisions and video pictures as well as induction motors that will run with less efficiency and may heat up. Clocks and timers will not operate accurately. Some AC loads are not affected by the harmonic distortion in the waveform. However, these inverters will not operate an induction motor as efficiently as a sine wave inverter because the energy of the additional harmonic is dissipated in the motor winding. Sine wave inverters produce an AC waveform as good as that from electric utilities. They can operate any AC appliances or motor within their power rating. In general, any inverter should be oversized by 20% compared to total AC loads are run at the same time to increase reliability and lifetime. This also allows for modest growth in load demand. From Figure 4.17, the square wave has a low peak voltage characteristic, but the modified sine wave begins to be approximately sinusoidal with a higher peak voltage. The sine wave is the conventional power's waveform. The waveform is a common frequency of a 50 H_Z and common root mean square (RMS) voltage of 220 V. This is the conventional grid voltage (lower).

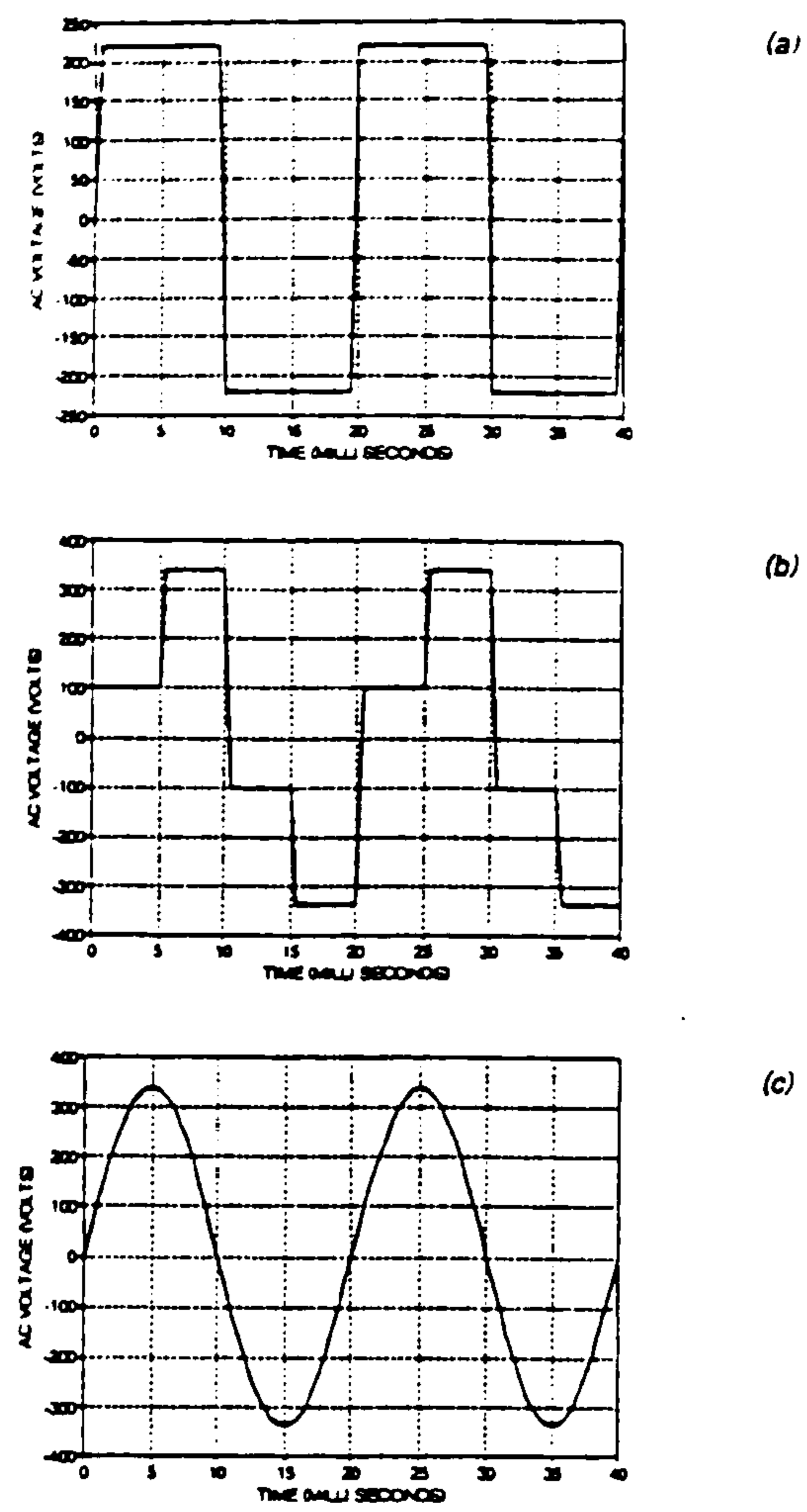


Figure 4.17 AC output's waveform of inverters. (a) square wave, (b)modified sine wave, (c) sinusoidal wave

Inverters have a standby consumption of electricity when the appliances are switched off. Therefore a good feature to include in a power inverter is automatic switching off when appliances are not in use. This avoids wasting electricity while the inverter is on standby. Normally, inverters generate high voltage AC power from lower voltage DC sources by chopping the DC voltage using switching components at high frequency, and then stepping up the chopped DC signal through a transformer. At present, most inverters use solid-state devices for switching the DC input. Silicon controlled rectifiers (SCR) and field effect transistors (FET) are both used. The main inverter design can be described as follows:

(a) Transistor Based Square Wave Inverter

Power transistors are the main switching devices that are paralleled to handle higher power. The power lost due to the transistors is quite high, due to the current required to drive the transistor bank. The surge power capacity is limited to 10% of the continuous power by the transistors' operating region. Although the cost of the square wave inverter is cheaper than the sine wave inverter, the square wave output has a high harmonic content. FET does not require a large current to drive it with on and off state. Paralleling the FET is simple and reduces the power losses. SCR can handle higher power than transistors and an SCR inverter is likely to be more robust. It can also handle high surge current, and due to the smaller control signals that are required, efficiencies are likely to be higher.

(b) Transistor Sine Wave Inverters and Pulse Width Modulated (PMW)

The sinusoidal waveform is generated by filtering a quasi square output waveform. Ferro resonant transformers and tuned filters are used. The filters are specially designed and constructed with capacitors that are resonantly operated at 50 H_Z. For a high frequency technique using transformers is called the "Pulse Width Modulated (PWM)". The PWM power inverter is realized by driving an inverter constructed with a high frequency buck-boost chopper in the discontinuous condition mode (DCM) [30]. As a result, the power generated by the PV array can be transferred to the load and the utility line under any array voltage. Next, an isolation between the PV array and the utility line is performed by a small high frequency reactor operating as an energy storage element. Finally, unity power factor can be provided and there is no need of a compensatory device to link the utility line. As can be seen from Table 4.6, this is a standard item of electronic device or equipment used in different applications. The input power is the DC power from the PV generator or battery and the output is AC power used to run AC appliances or feed into the utility grid. The efficiency of the inverter usually depends on the load current being a maximum at the nominal output power. It can be as high as 95% but will be lower if the inverter runs under part load.

Table 4.6 Inverter parameters

Parameters	Line-commutated inverters	Self-commutating PWM inverters
High unit power availability	Yes	No
High voltage operation	Yes	No
Cost	Low	High
Reliability	High	Low
Ability to operate stand-alone (during grid black out)	No	Yes
Harmonics content	High	Low
Need for power factor correction	Yes	No
development status	Technology standard	Require R&D
Space require	Large	Small

The vast majority of inverters for PV applications can be broadly divided into three types (see Figure 4.18 a, b, c). Variable frequency inverters are used for stand-alone devices and shaft power applications, almost exclusively in PV pumping systems. Other types are suitable for the grid connection of the PV power system. Fixed frequency inverters (self-commutated) are able to feed an isolated distribution grid and, if equipped with special paralleling control, also a grid supplied by other parallel power sources. Fixed frequency inverter (line commutated) is able to feed the grid only when the grid frequency is defined by another power source connected in parallel. The inverter will not work if the external frequency reference is lacking. The advantages and disadvantages of these inverter types are summarized in the table above.

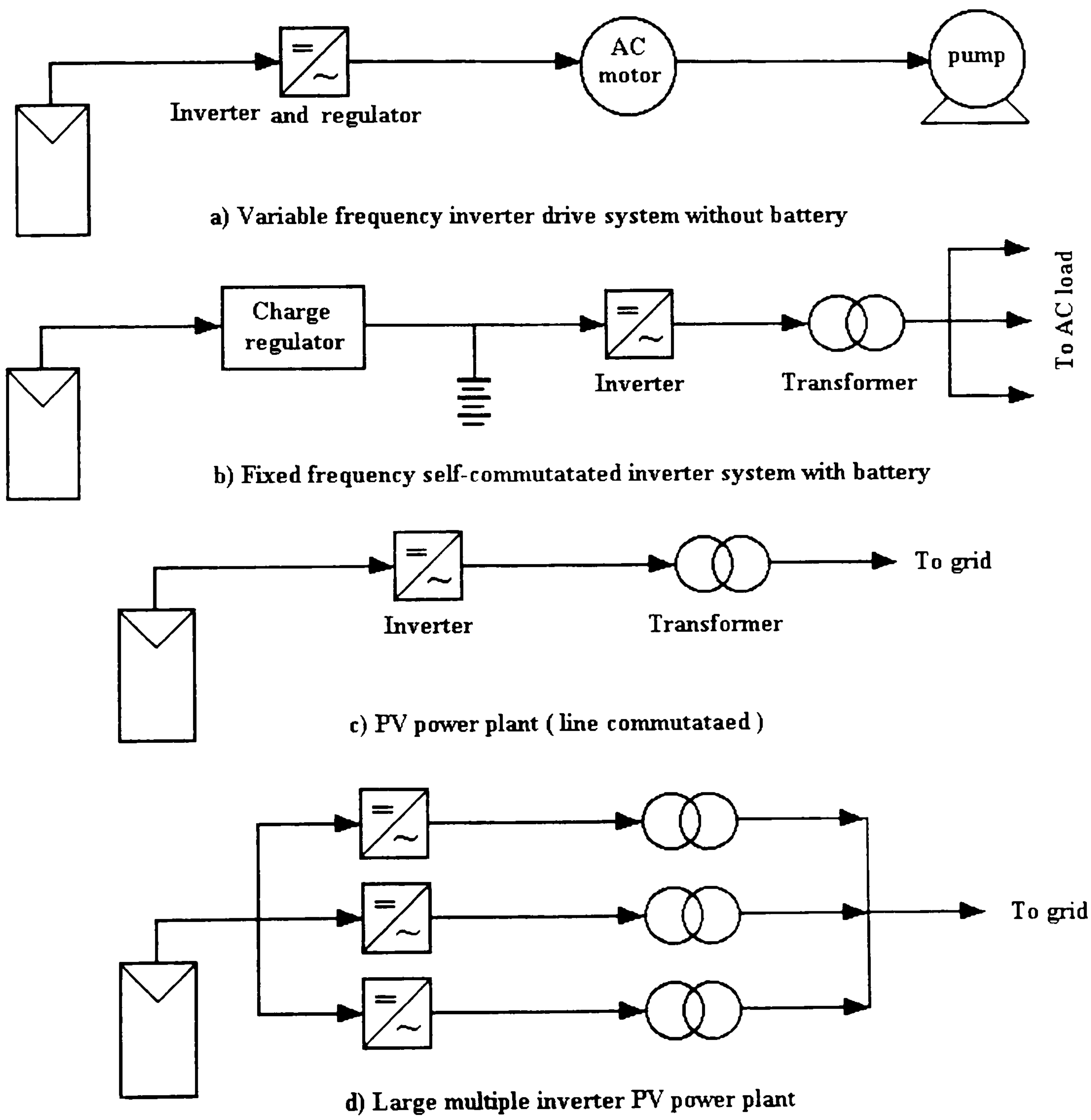


Figure 4.18 Various inverter configurations

The inverter should be installed in controlled environment because high temperature and excessive dust will reduce lifetime and may cause failure. The inverter should not be installed in the same enclosure as the battery bank. This is because the corrosive gassing of the batteries can damage the electronic devices and the switching in the inverter that might cause an explosion. However, the inverter should be installed as close as possible to the battery to keep minimum resistance losses in the electrical wires. Both input and output circuits of the inverter should be protected with fuses or circuit breakers. These safety devices should be accessible and clearly labeled. Using a surge protection device on the inverter input to protect against nearby lightning strikes is recommended.

4.5.3.2 Specifications

The choice of inverter will affect the performance, reliability and cost of the PV system. Usually, it is the third most expensive component after array and battery cost. Good selection of inverters for stand-alone PV systems should mainly consider the following: (i) input and output voltage, and output waveform, (ii) power conversion efficiency, (iii) rated power, (iv) duty rating, (v) voltage regulation, (vi) frequency, (vii) power factor. The manufacturers' specification sheets will list some of the following parameters.

a) ***Power Conversion Efficiency:*** This value gives the ratio of output power to input power of the inverter. The efficiency of stand-alone inverters will very significantly with the load. Values found in manufacturers' specifications are the maximum that can be expected. The DC-AC conversion efficiency depends on the load size, load type and sometimes on battery DC voltage. Most inverters reach maximum efficiency at between 1/3 and 2/3 of their rated capacity.

b) ***Rated Power:*** Power can be measured in Watts, but volt-ampere (VA) is the unit that is commonly used for the inverter because it reflects the actual power handing capability of these devices. Small inverters are usually rated for continuous power. However, they are not often used for inductive loads that require high starting surges. When selecting an inverter it is necessary to know the continuous power demand for the range of appliances likely to be used at any one time. It is also necessary to know the starting power requirements for these appliances. Before choosing an inverter, check the maximum size motor rating that can be started by the inverter while supplying other appliances that would be operated simultaneously.

c) ***Duty Rating:*** This rating gives the amount of time the inverter can supply its rated power. Some inverters can operate at their rated power for only a short time without overheating. Exceeding this time may cause hardware failure.

d) ***Input Voltage:*** This is determined by the total power that is also required by the AC loads and the voltage of any DC loads. Generally, the larger the load, the higher the input voltage of inverter that will be needed. This keeps the current at levels where switches and other components are readily available. As previously mentioned, stand-alone inverters typically operate at 12, 24, 48, 120 and 220 VDC input.

e) ***Surge Capacity:*** The ability to provide up to six times the rated power will enable the inverter to shunt loads with high starting power demands and the inverter will not have to be oversized for normal operation. Most inverters can exceed their rated power for a limited time (seconds). Surge requirements of specific loads should be determined or measured some transformers and AC motors require starting currents several times their operating level for a few seconds.

f) ***Standby Current:*** This is an amount of current (or power) that is used by the inverter. This is an important parameter if the inverter will be left on a long time to supply small loads. The inverter efficiency is lowest when load demand is low.

g) ***Voltage Regulation:*** This indicates the variability in the output voltage. Better units will produce a nearly constant RMS output voltage for a wide range of loads. A regulated output voltage maintains the RMS voltage close to 220 volts and the peak power near 380 volts to ensure that no appliances are damaged.

h) ***Voltage Protecting:*** The inverter can be damaged if DC input voltage levels are exceeded. Many inverters have sensing circuits that will disconnect the unit from the battery if specified voltage limits are exceeded. However, voltage protection can be divided into two conditions. Firstly, with over voltage protection, the inverter will be protected if the battery voltage rises too high. Secondly, with under voltage protection, the inverter will shut down if the battery voltage falls too low. It also helps to prevent deep discharging of the battery bank.

i) ***Frequency:*** Most appliances in Thailand require 50 H_z (standard frequency level in Thailand). High quality equipment requires a precise frequency as regulation variations can cause poor performance of clocks and electronic timers. An inverter designed to use in Thailand must ensure that the AC frequency is consistently 50 H_Z.

j) ***Modularity:*** In some systems it is advantageous to use multiple inverters. These can be connected in parallel to service different loads. Manual load switching is sometimes provided to allow one inverter to meet critical loads in case of failure. This added redundancy increases system reliability. Furthermore, when the load demand is extremely variable it is difficult to choose an inverter that is efficient over the whole power range. When inverters operate in parallel, only those inverters that are required will turn on, while the others will wait in standby mode.

k) ***Power Factor:*** The cosine of the angle between the current and voltage waveforms that are produced by the inverter is called the "power factor". A power factor of unity means that the voltage and current are totally in phase for resistive loads the power factor will be unity. Usually, the most common load in a residential system is inductive load. The power factor will sometimes drop as low as 0.5 and lower power factors mean that the current lags the voltage waveform.

4.5.4 Monitoring and Measuring System

The data monitoring of the system is the principal tool for the evaluation of the installation, and is also used as a first step in the detection of faulty modules. The main hardware for a complete system should comprise microcomputer set, magnetic disk, printer, measurable instruments, analog/digital converter, control board and so on. The hourly data must be recorded on magnetic disk and can be printed out.

The necessary data will need to record the following data.

- Global horizontal radiation.
- Radiation in the tilt angle of the array.
- Maximum wind speed.
- Average wind direction.
- Cell junction temperature.
- Array output energy (output of the sub-arrays).
- Energy supplied to each load.
- Battery voltage and state of charge.
- Power conditioning data (regulator and inverter).

The operation of switches and alarms should be recorded including the control voltage/current to load. They have to be displayed by indicating instruments on the main switchboard. An error message must be recorded and printed out for indicating faults. The main aim of the monitoring system is to collect all data regarding energy, meteorology to put those in shape, then to visualize them on a synoptic panel while being tape recorded.

All this is only necessary for full analysis of the system. For a centralised PV mini-grid system in a Thai rural village reduced monitoring can be used for severe fault sensing and operation because full measuring systems are the complex and expensive systems.

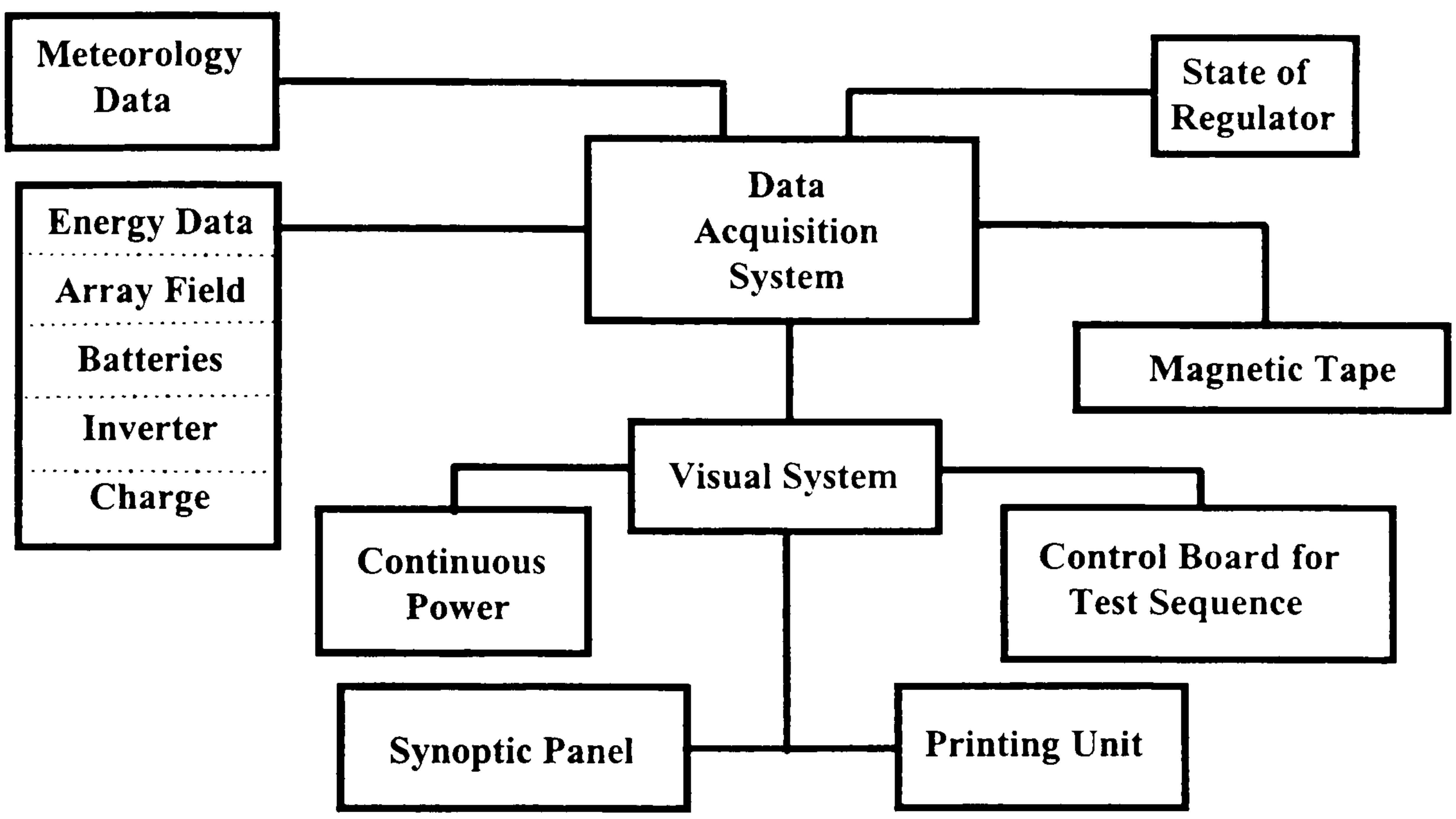


Figure 4.19 A sample monitoring system that is possibly used in a PV system.

4.5.4.1 Monitoring Approaches

Table 4.7 provides a suggested list of daily and monthly (recording) performance data. The designer must review the contractual requirements for plant monitoring, including the allocated budget, when selecting the parameters to be acquired and recorded.

Table 4.7 Daily and monthly performance data : A general list for all PV plants [6]

Parameters	Units	Parameters	Units
A) Monitoring Information		**E) Battery Information**	
- Hours of monitored data	h	- Daily average cell temperature	°C
- Missing data	%	- Daily average DOD	%
		- Recharge fraction, Ah	%
B) Solar and Meteorological Data		- Recharge fraction, Wh	%
- Daily average global solar radiation	kWh/m^2	- Number of charge/discharge cycles	-
- Daily total global solar radiation	kWh/m^2	- Average discharge voltage	VDC
- Daily average solar radiation (tilted)	kWh/m^2	- Lowest discharge voltage	VDC
- Daily total solar radiation (tilted)	kWh/m^2	- Average charge voltage	VDC
- Sunlight average irradiance	kW/m^2	- Lowest charge voltage	VDC
- Peak sunlight irradiance	kW/m^2	- Peak voltage	VDC
- Sunlight average irradiance (tilted)	kW/m^2	- Highest cell voltage	VDC
- Peak sunlight irradiance (tilted)	kW/m^2	- Discharge capacity	Ah
- Daily average ambient air temperature	°C	- Charge capacity	Ah
- Lowest ambient air temperature	°C		
- Highest ambient air temperature	°C	**F) Power Conditioning Information**	
- Daily average wind speed	m/s	- Daily average inverter energy	kWh
- Lowest wind speed	m/s	- Total inverter energy	kWh
- Highest wind speed	m/s	- Daily average inverter power	kW
- Theoretical sun hours	h	- Inverter energy efficiency	%
- Measuring sun hours	h	- Peak inverter power efficiency	%
- Daily average sun hours	h	- Converter efficiency	%
		- Total converter efficiency	%
C) Plant/System Information		- Inverter on time	h
- Total load energy	kWh	- Converter on time	h
- Total energy to grid	kWh		
- Total energy from grid	kWh	**G) Load Information**	
- System energy efficiency	%	- Daily average input current at load	AAC
- Plant availability	%	- Daily average input voltage at load	VAC
- Plant capacity	%	- Daily average frequency of load	H_Z
		Example for pumping load	
D) PV information		daily average flow rate	l/s
- Daily average array energy	kWh	daily total volume	l
- Total array energy	kWh	pump on time	h
- Array energy capability	kWh	daily average pressure pump	bar
- Array utilization factor	%	daily average input current to pump	AAC
- Daily average array power	kW	daily average input voltage to pump	VAC
- Peak array power	kW	daily frequency of pump voltage	H_Z
- Array energy/efficiency	%		
- Daily average module temperature	°C		
- Peak average module temperature	°C		

In the selection of the appropriate data acquisition system (DAS), the designer should compare the monitoring requirements against the capability of the DAS. including its field performance record. In defining the different types of measurements to be recorded, it is important to consider different sizes of PV plants, subsequent analysis required to satisfy the aims listed in Table 4.7, and the equipment devices currently available on the commercial market. The relative applicability and characteristics of the different types of monitoring can be identified as follows [6]:

(i) ***Type I*** *: Monitoring of Demonstration or Commercial Plants with Few or No Scientific Goals and Minimum Evaluation.*

- Measurement and/or recording of energy parameters only to give a rough indication of the PV system performance.
- Use of simple data loggers or energy meters to record the energy data on and hourly basis, or only one set of data per day to save storage memory. Manual data taking on a permanent basis is not recommended, except for very small low cost PV systems, even for user-motivational purposes. Reliable energy counters are necessary for this type of monitoring to be effective.

(ii) ***Type II*** *: Monitoring of Plants without In-depth Performance Evaluation*

- Minimum number of kWh counters to reduce costs.
- Only voltages, currents and inverter output/utility energies (energy computation done with an off-line PC using V and I to avoid the cost of energy counters).
- Use of a simple data logger with or without modem data transfer.

(iii) ***Type III*** *: Monitoring of Plants with an In-depth Performance Evaluation*

- All of type I and II measurements plus:

  -Ambient air temperature

  -PV module temperature

  -Wind speed (including peaks)
- Use of either a sophisticated data loggers like a PC based system with or without modem data transfer.

(iv) ***Type IV*** *: Monitoring of Plants with an In-depth Analysis of Plant Performance and of Recorded Data*

- All of type III measurements plus:

  -Energy counter data for redundancy and accuracy

-Peak values of solar irradiance, wind speed, PV power output, and minimum and peak battery voltages.

-Individual battery cell voltages (other battery cell parameters such as specific gravity or electrolyte level may be included).

- Display of on-line real time data on PC/video monitor
- Storage of real time calculated parameters (power, energy, averages)
- Scanning of peaks and minima
- Use of PC-based system with or without modem data transfer

Table 4.8 Classification of data measurements and recording on typical stand-alone and Grid-connected PV plants [6].

Measurements	Monitoring Classification			
	Type I	Type II	Type III	Type IV
1) Solar and Meteorological				
♦ Solar irradiance (power)				
-Horizontal		*	*(p)	*(p)
-Tilted		*	*(p)	*(p)
♦ Solar irradiation (energy)				
-Horizontal				
-Tilted	*			*
♦ Wind speed		*	*(p)	*(p)
♦ Ambient air temperature		*	*	*
2) PV array				
♦ Voltage and current		*	*	*
♦ Power			*	*(p)
♦ Energy	*			*
♦ Temperature, PV module			*	*
3) Battery				
♦ Voltage and current		*	*	*(p,m)
♦ Power			*	*
♦ Energy	*			*
♦ Cell voltages				*
♦ Cell temperature		*	*	*
4) Inverter/Converter				
♦ Output voltage and current		*	*	*(p)
♦ Output power			*	*
♦ Output energy	*			*
5) Auxiliary Power Sources				
♦ Output Energy	*	*	*	*
6) Rectifiers (Battery Charging)				
♦ Output voltage and current		*	*	*
♦ Output power			*	*
♦ Output energy	*			*
7) Utility grid				
♦ Energy to grid	*		*	*
♦ Energy from grid	*		*	*

Note: All recorded values with check marks (*) are average for each duration of scanning and recording time, except for discrete (digital) data, e.g., energy, peaks and minima.
(p) = Peak value during the averaging interval recorded.
(m) = Minimum value during the averaging interval recorded.

In the case of a centralised PV mini-grid system in a Thai rural village, the basic monitoring and measuring functions required should be based on monitoring classification type I in Table 4.8. This is because

(i) full measurements are the complex and expensive systems.

(ii) the cost of instrumentation can add significantly to the total cost of the balance of system (BOS). Therefore, to minimise the BOS costs, the data to be collected and displayed must be limited to absolutely essential measurements. Minimum measurements are needed to ensure that the basic safety of PV hardware and cover maintenance and operation needs.

(iii) Simple calibration procedures can be used on site by Thai local technicians.

When designing a control system for a centralised PV mini-grid system in a Thai rural village, the following guidelines should be considered:

- Reduce the power consumption of instruments and controls. Their impact on the overall energy balance of a PV system is significant, since usually they are kept operating 24 hours per day.
- Design for worst-case (maximum) temperatures and foreseeable tolerances in order to compensate for bad calibration of instruments and signals.
- Provide for appropriate protection of electronics.
- Implement system diagnostic features by comparing the controller output and the corresponding feedback from plant.
- Provide a reliable power supply, such as a UPS (Uninterruptible Power Supplies), to crucial instrumentation and controls.
- Overvoltage protection should be provided on power supply and signal lines. All signal wires should be isolated from power circuits. All equipment shielding and negative polarity cables should be properly grounded.
- Provide a manual override capability for each crucial control function implemented automatically.

4.6 Design of the Array Supporting Structure and Installation

The installation of the PV array can be mainly divided into two separate tasks, namely physical and electrical. The physical installation will involve the mounting of the solar modules on a sturdy frame that will maintain the array's tilt and position throughout the worst weather. The electrical installation entails wiring the modules that are connected in parallel and series configuration to the load. However, the array structures as the mechanical part of PV arrays still consume a high percentage of total plant costs. The step of research and development (R&D) and demonstration projects to large scale application of PV energy lead to the necessity of standard, reliable and aesthetic low cost array structures that only need to be adapted to on site conditions. Nevertheless, new innovative structural designs are still needed and should be pursued under an R&D programme.

4.6.1 Photovoltaic Array Field and Wiring

As previously designed in this project, the PV array field for a centralised PV mini-grid system consists of 240 modules. The connection of the PV array for this design is illustrated in Figure 4.20. It shows the number of modules connected in series in a string is 15, and there are 16 strings (8 sub-arrays) in an array field, also illustrated in Figure 4.21.

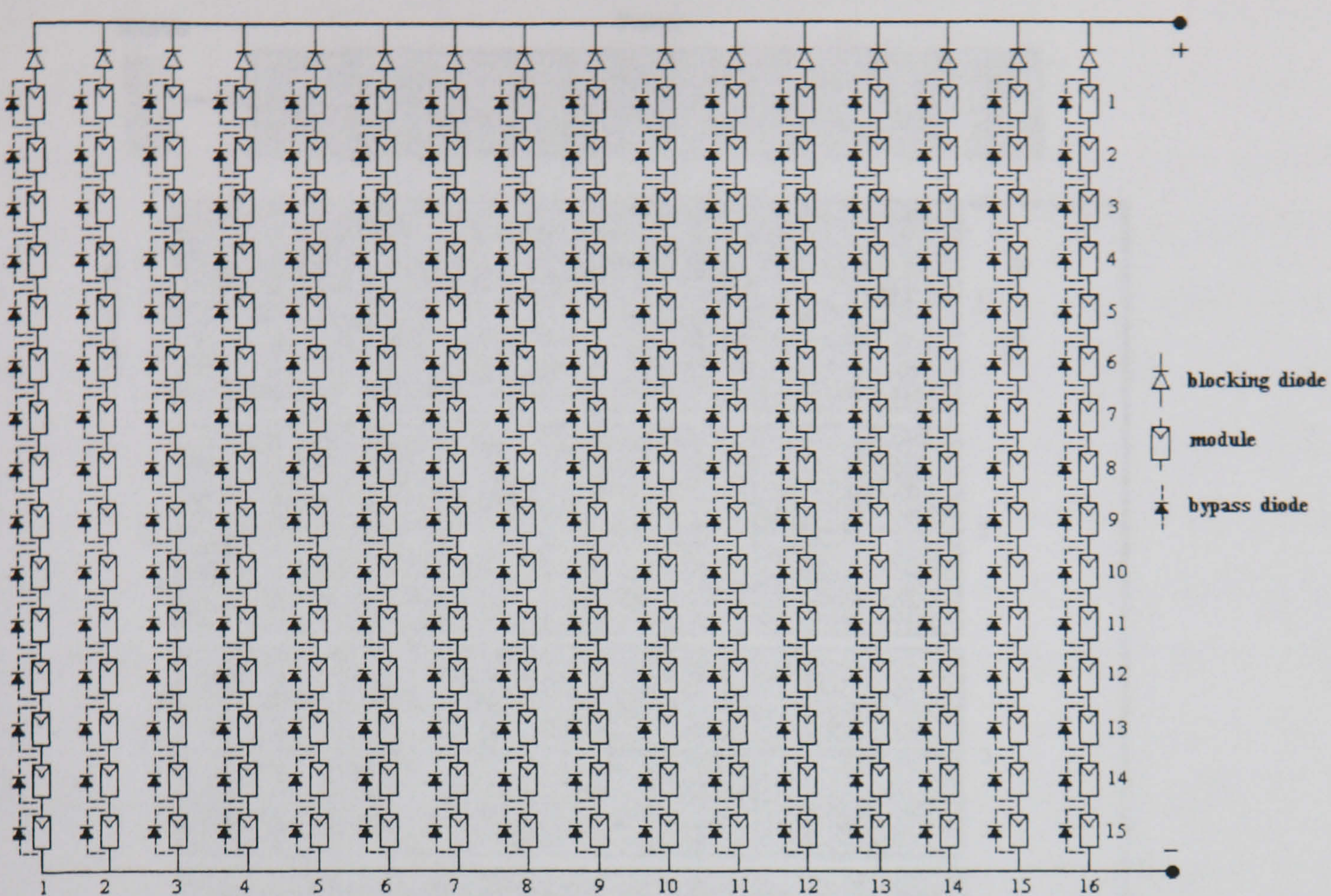


Figure 4.20 Solar arrays are interconnected in the centralised PV mini-grid system based on daily load demand in the sample village at Udon Thani province of Thailand

The modules are interconnected electrically by cables with suitable size. The beginning and end of each string will be connected to the string junction box (terminal box) by special connector cables. The module connector plugs should be provided to facilitate the system integration. An additional securing sleeve prevents this type of plug being opened by unauthorized person. This securing sleeve will be clamped to the module frame and the connecting cables are fixed additionally. However, designing the cabling of an array field is one of the most important design aspects of a PV system because it will give low cable losses, easy survey of the array field, easy maintenance and easy fault location. The outgoing cables from each terminal box of each string need to run underground to the main control building. In addition, the frame of each module must be grounded for safety. PV modules should be installed in a fashion that allows easy excess for repair and maintenance. In practice, solar cells operate more efficiently at lower temperature. Consequently, the modules should be installed in a way that will keep them as cool as possible during daytime operation. Support structure costs are dependent on area rather than wattage. The required area is a function of the required PV power and gross module efficiency.

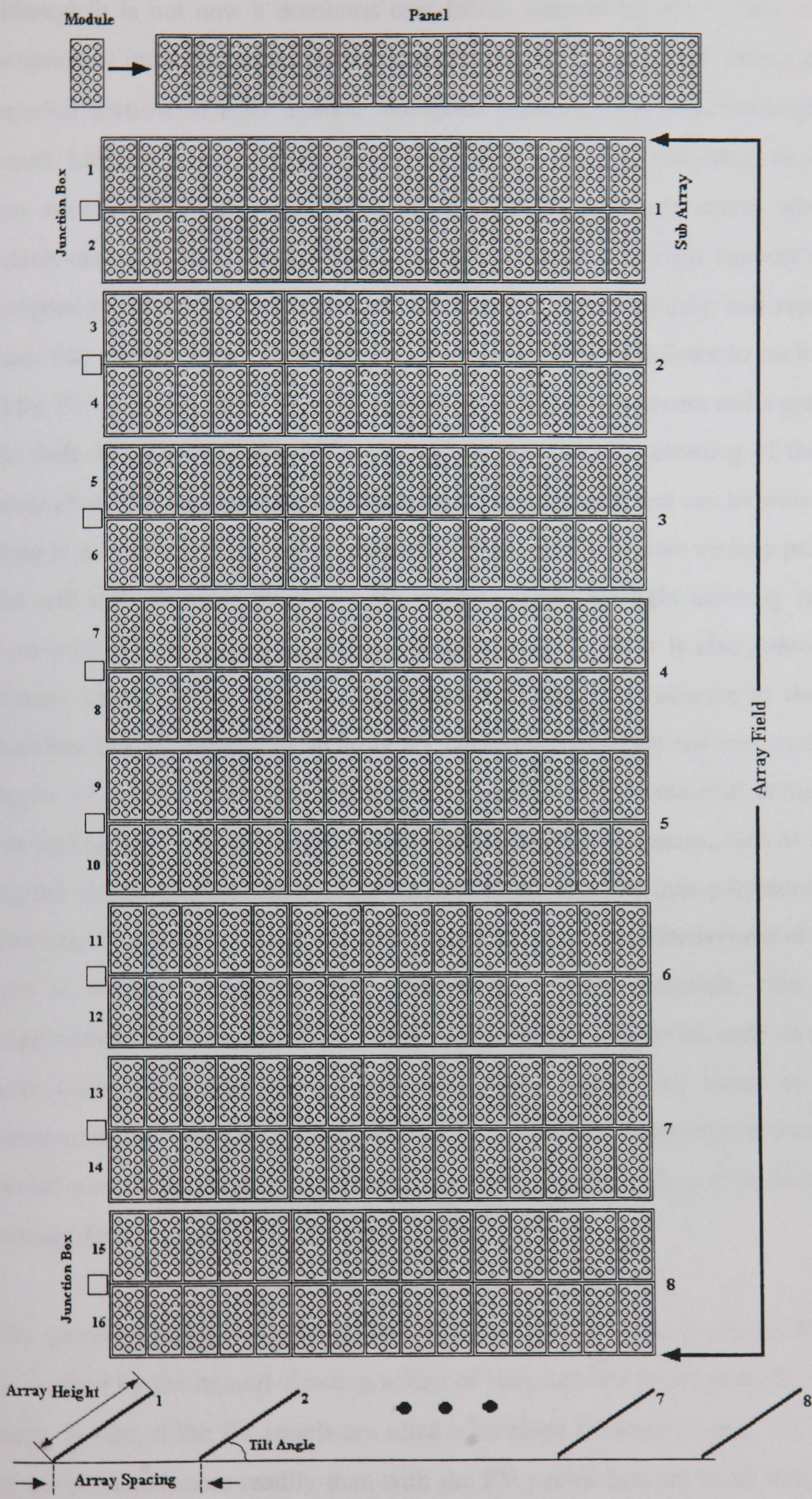


Figure 4.21 A solar array field arrangement based on Figure 4.20

Although it is not now a dominant cost factor, support structure costs will become increasingly important as module prices decline. PV array repair during the 20 year expected lifetime of a PV system will entail replacing modules whenever a failure occurs. Large portions of an array can malfunction when an individual module fails it may necessary to remove modules for inspection and replacement when module defects occur. If the hardware that attaches the modules to their support structure is designed to allow for easy removal, the task of troubleshooting and repair will be made that much simpler. Nevertheless, in this case, a suitable fence to enclose the area of the PV array should be installed to prevent unauthorised access and a problem from the theft. Maintenance of a PV array will include periodic cleaning of the module's cover glass. For Thailand, in the winter time the snow problem can be waived because there is no snow in Thailand. However, airborne dirt is a more serious problem. The dirt will soil the cover glass of a PV module. Thus, the light intensity reaching the solar cells will be reduced and the current or output power is also reduced. Soiling reduces output power by reducing the transmission of irradiance to the cells and therefore can be modeled as an array I-V curve translation for reduced irradiance. The degree of soiling is strongly a function of module surface material composition the site soiling level, and the frequency of natural cleaning processes, such as rain, unless regular cleaning is provided. Glass tends to retain dirt less than polymeric materials. The rate of soil deposition is material independent, but the effectiveness of removal by rain is material dependent [31]. For heavily soiled materials, rain can cause improvements in transmission of 10-15% in hard cover material, such as glass. Long term soiling loss can be approximated as a constant loss based on the above parameters. For urban sites the average losses in relative transmittance over a one year period were 7-8% for glass and higher for soft materials, such as silicone rubbers. The average for a non urban site for glass is about 3% [32].

The quantity and type of soiling depend on the site's location however, some dirt can be washed by the natural cleaning action of rain, but this depends on the slope of the array. In fact, if the PV panels are tilted with slope between 0° and 10°, the soil will be accumulated more readily than with the PV panels that are tilted with slope more than 10°. Theoretically, the energy conversion efficiency of a silicon cell increases with decreasing of temperature at a typical rate of approximately 0.5%.K^{-1} (relative) of the 25°C value (i.e., a cell with a 10% efficiency at 25°C will have an efficiency of 9% at 45°C). The daytime temperature of a solar cell or module is governed by the solar radiation, the ambient temperature, and the amount of ventilation or heat transfer available. The last factor is the only one that is somewhat under control and depends on the kind of environment in which the solar modules are placed. It is assumed that PV modules are mounted in such a way that there is ventilation on both their tops and back. They will operate as much as 20°C cooler than if they are mounted flat on a surface. In the case of PV modules mounted in Thailand, the PV array will be positioned facing south in a place where sunshine will not be blocked.

4.6.2 Conceptual Design of PV Supporting Structure

Wind speed in Thailand is varies from 1.1-5.4 m/s at 10 metres reference height and estimates of power densities of surface winds over the whole country are typically in the range 10-20 W/m^2 [33,34]. The quantity and type of materials used and the installation time should be kept to a minimum to reduce the hardware and labour cost. A various of factors must be considered when PV array supporting structure is designed. The main boundary conditions can be written as follows:

- Module size.
- Maximum wind speed.
- Tilt angle.
- Type of mounting (either tracking or non tracking)
- Minimum allowed distance between panels.
- Ground clearance.

The size of the solar module and its shape must be known to arrange a size of panel or sub-array. Wind velocity plays an important role in minimizing array structure costs, whenever a plant is erected on top of a hill, the influence of wind load will increase on cost because of high wind load. In general, the highest wind loads occur on the first row of the array. The downwind arrays are protected by the first array resulting in lower wind loads, whereby the wind protection increases with higher tilt angles. Furthermore, with increasing ground clearance the average net pressure on the panel surface increases owing to higher wind loads. The simplest sort of PV array is exclusively made from flat PV panels that are set in a fixed position. Usually, panels are placed to face south (in the northern hemisphere) and are tilted at an angle from the earth's surface approximated by the angle of latitude at the design location. However, a flat-plate array that is fixed may be simple, but it is not necessarily lowest in cost. This is because it points in a single direction and usually receives the sun's rays obliquely (sometimes manual adjustment for seasonable variation of the sun's position is provided). Generally, the support system design loads will include any loads, such as dead load, live load, wind load, snow load and earthquake load. The dead load is usually well known and consists of the weight of PV panels and supporting structure. Live load represents maintenance and washing activity on the PV system. The snow loading criterion depends on site location, structure configuration, nearness of adjacent structures, wind velocity and moisture content of the snow (for Thailand, this can be disregarded). Earthquake forces are due to a combination of structure mass and ground support acceleration [35]. Foundation design and cost should consider the following factors, for example stability, safety factor and soil properties. Stability refers to the foundation's ability to resist overturning, sliding and direct uplift due to wind load. The repair cost and acceptable degrees of power outage should be considered in the safety factor.

As previously designed in this project, the sub-array is composed of 2 panels (30 modules) in an array (see Figure 4.21). The PV supporting structure design depends on module size including sub-array and array size. A schematic drawing of a supporting structure is shown in Figure 4.22. It is a sample design for a typical supporting structure in a PV system and can be used in this project. The details of the supporting structure can be illustrated as follows:

- The angle of inclination is simply achieved by choice of the appropriate bolt position on the column.
- Adjustment of the angle of inclination is easily achieved by transfer from one bolt position to another.
- Three or four angles of inclination are available (latitude angle, optimum angle, suitable angle in the summer and winter). Study in the reference [36] indicated

that the optimum module size for large scale application is of the order of 1.2 X 2.4 m.

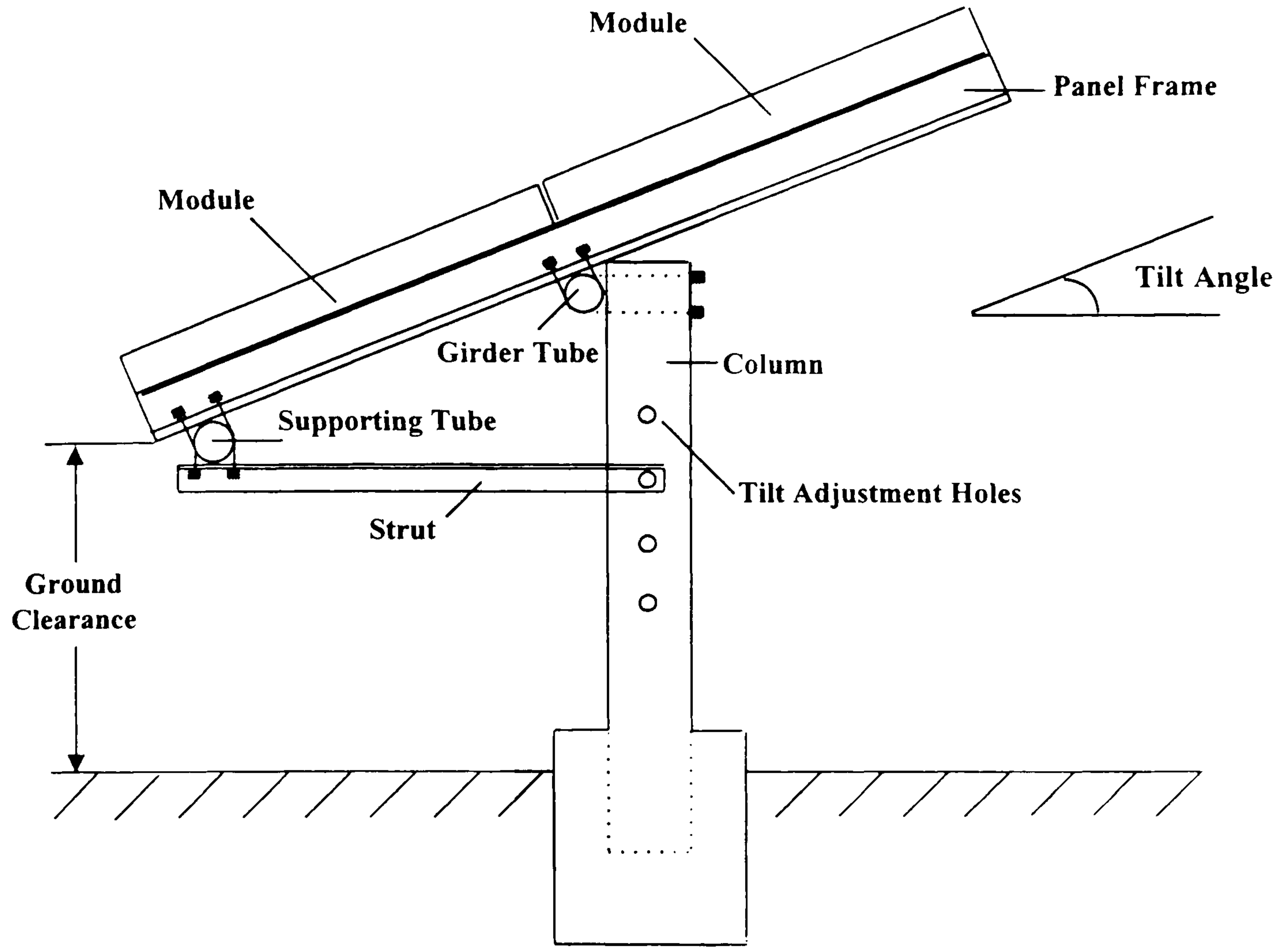


Figure 4.22 Schematic drawing of the structure designed based on Figure 4.21.

A large number of different approaches have been considered for support structures. The most severe load placed on this support structure is wind loading, with the design wind loading largely determining its cost. The low profile of photovoltaic arrays and the aerodynamic shielding provided by adjacent rows in an array field or by a surrounding fence act to greatly reduce these loads. There are four main shapes of column that can be used to reduced the structure cost [37], for example U-profile, I-profile, L-profile and Z-profile. For all array chord lengths are examined, except for 0.7 m, the U-profile proved to be the lowest cost solution.

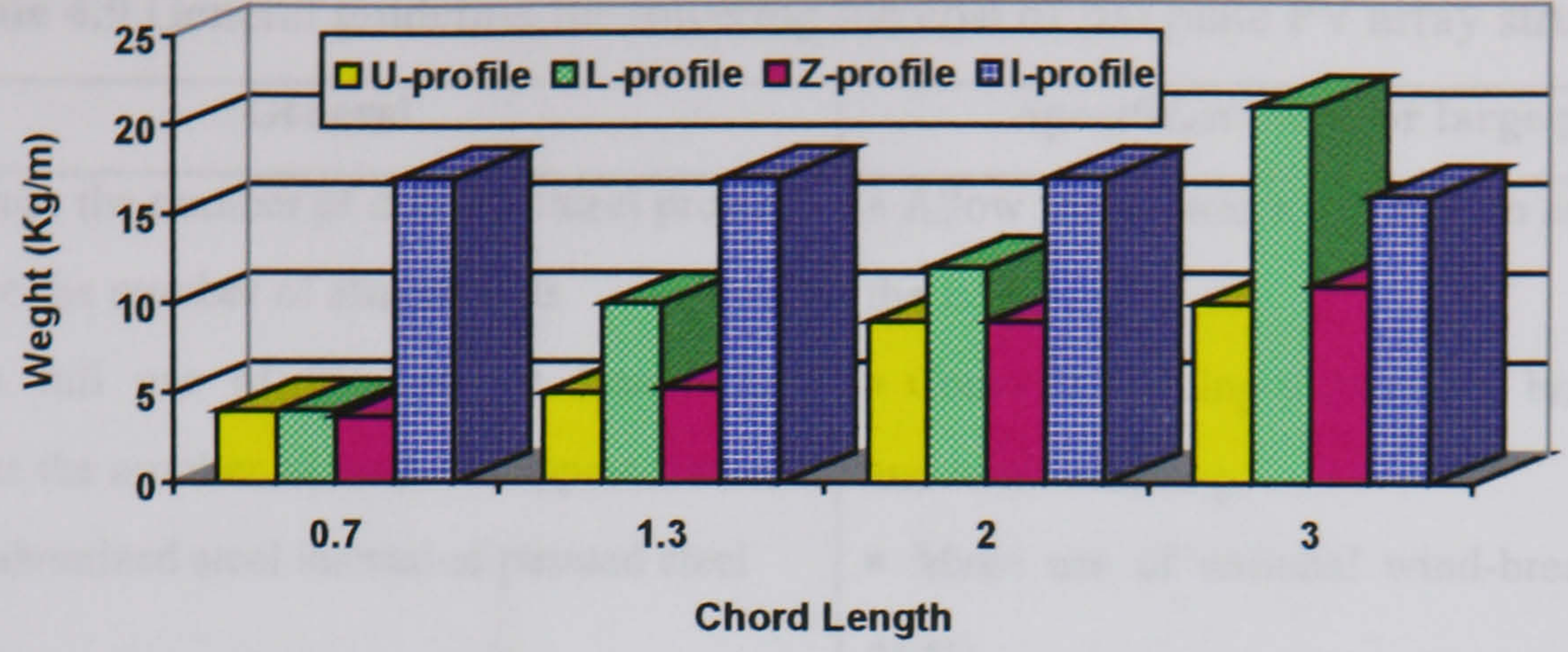


Figure 4.23 Specific weight of column in different steel profiles for identical bending moments [37].

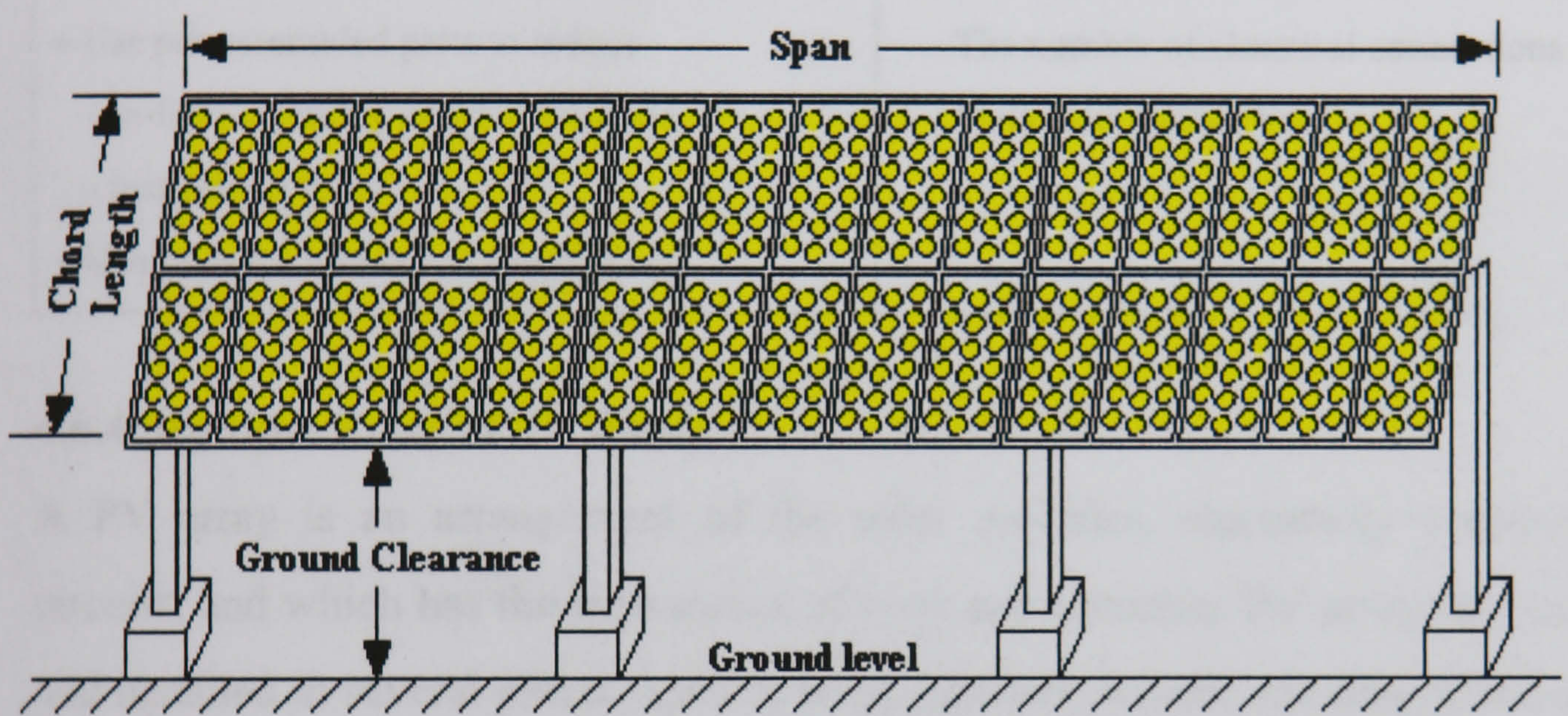


Figure 4.24 Installation of the PV solar panel (a sub-array) is based on Figure 4.22.

The array structures used in Europe are predominantly fixed, tilt angle designs for flat plate modules. Experience with tracking system is limited. A wider dissemination of tracking systems will depend on long-term reliability and energy output advantages demonstrated by existing plants. The trend in the fixed structures is towards single-pedestal structures with galvanized steel because of proven low cost results [6,37].

4.6.3 Guidelines for PV array structures

Table 4.9 lists a set of guidelines for PV array structures. They are generally applicable to all sizes of PV array and especially for future low cost array structures.

Table 4.9 General guideline for lowering the cost of flat plate PV array structure [6]

General	Specific, mostly for large plants
• Minimise the number of different steel profiles • Reduce the number of attachments • Make full use of PV module frames and minimise the number of module support frames • Use galvanized steel instead of painted steel	• Allow for a lower wind load on arrays inside the field. • Consider erecting a fence for both protection and wind breaking • Make use of national wind-breakers (if any exist)
• Use stainless steel bolts and nuts, especially in regions with a salty environment (to achieve long life, thus reducing cost) • Use pre-assembled parts to reduce - In-field assembly and cabling time - Installation time • Minimise the number of foundations	• Use large PV module (W_P) to reduce: - Material requirement - Attachments (bolts, nuts and washers) - The number of electrical connections - Field installation costs

4.6.4 Multiple Rows of PV Panel

A PV array is an arrangement of the solar modules, electrically connected into circuits, and which has the appearance of rows and columns. PV arrays are fabricated and installed in several pieces, such as solar modules, panels, sub-arrays and so on. A solar panel is composed of modules, wiring, sub-panel supporting structure. However, solar modules are the main components of the PV array the panel wiring collects the electricity from all the solar cells and routes it into the panel terminals.

The layout of the array field was shown in Figure 4.21. The spacing between rows of PV panels (sub-array) must enough distance to avoid the shading effect due to angle of sun's rays, especially in the winter. Typically, the arrangement of panels into multiple rows is needed, when the size of the plant exceeds a few kilowatts in power. If PV arrays are to be arranged into multiple rows, they are usually placed in the East-West direction with the panels tilted toward the Equator. In the case of Thailand the panels must be tilted toward the south direction because the location of Thailand is located in the northern hemisphere. However, avoiding the reciprocal shadowing of panels at any time of the day and at any day of the year requires a suitable distance between rows and then a large area would be occupied by the PV plant. A seasonal compromise between avoiding shadowing and avoiding excessive distance between rows of panels should be that there is no shadowing at noon on the day of winter solstice. Using that condition, reciprocal shadowing occurs only in low radiation hours in some days in the winter, with a negligible decrease in the overall energy collected by the plant. Then minimum distance , W , between rows of panels is given by:

$$W = h \{ \sin\beta \tan(\delta_w + L) + \cos\beta \} \tag{4.6}$$

where :

- h = the height of the panel
- δ_w = 23.5° is the solar declination at the winter solstice
- β = tilt angle
- L = latitude

Using the equation above, the ratio of minimum distance between rows of the panel to that on height of panels (W/h) can be plotted in the figure below as a function of tilt angle β, for several value of site latitude, L ,

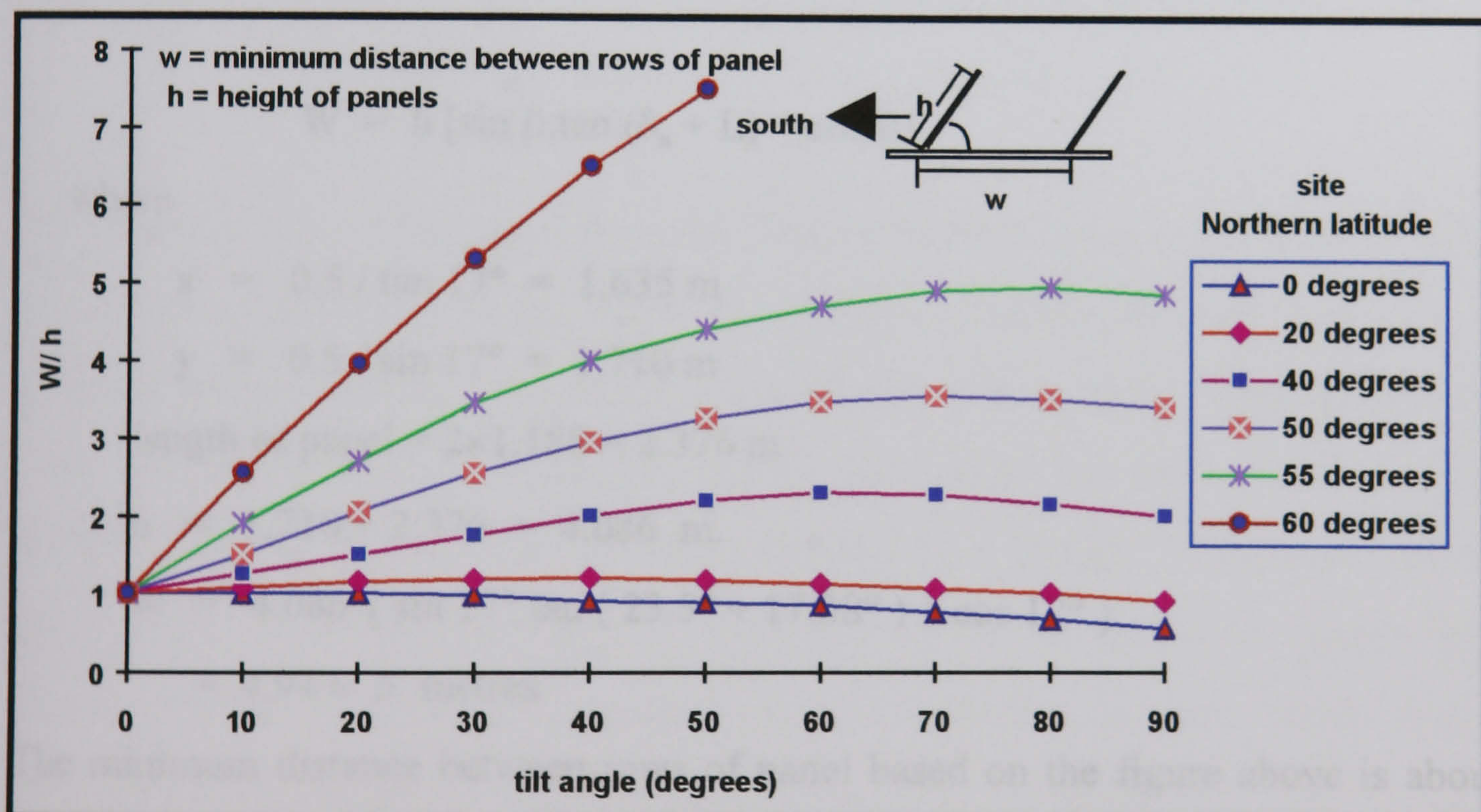


Figure 4.25 Minimum distance between rows of the PV panel on tilt angle

To determine the minimum distance between rows of panel in the sample village, the data in the figure above can be used to find this value, or can be found from Equation 4.6. The data of site latitude (L) and the height of the panel (h) are

Example:

Location: Udon Thani province of Thailand

Latitude: 17.38° N

Optimum tilt angle: 17°

From the information of a solar module type #BP585, its dimensions are 530 cm. (0.53 m.) wide and 1188 cm. (1.188 m.) long. If the PV array is arranged as shown in Figure 4.21 and based on the PV array supporting structure in Figure 4.22, this yields,

Array height (h) : y + length of panel

Ground clearance is 0.5 metre.

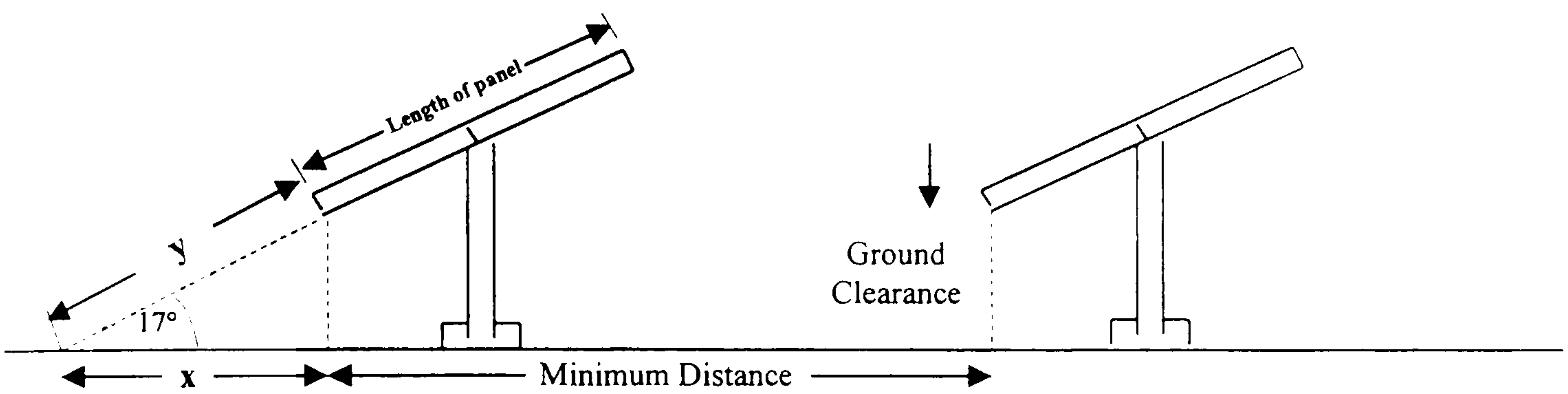


Figure 4.26 Minimum distance between rows of panel (the sample case)

$$W = h\,[\sin\beta.\tan(\delta_n + L) + \cos\beta]$$

where

$$x = 0.5 / \tan 17° = 1.635 \text{ m}$$

$$y = 0.5 / \sin 17° = 1.710 \text{ m}$$

length of panel = 2×1.188 = 2.376 m

$$\therefore\ h = 1.710 + 2.376 = 4.086 \text{ m.}$$

$$W = 4.086\ \{\sin 17° \tan(23.5° + 17.38°) + \cos 17°\}$$

$$= 4.94 \approx 5 \text{ metres}$$

The minimum distance between rows of panel based on the figure above is about 5 metres and this method can be applied anywhere. In the case that the PV panels are installed on the ground (ground clearance = 0), the minimum distance between rows of panel can be found by the same method as follows:

$$W = 2.376\ \{\sin 17° \tan(23.5° + 17.38°) + \cos 17°\}$$

$$= 2.87 \text{ metres}$$

Array shading is one of the causes of mismatch, it is caused either by other arrays or by foreign objects. The modeling of the array shadowing from the direct component of solar irradiance is straightforward and is easily derived using solid geometry. The degree of shadowing from other arrays is a function of array spacing, tilt angle, azimuth angle and tracking mode.

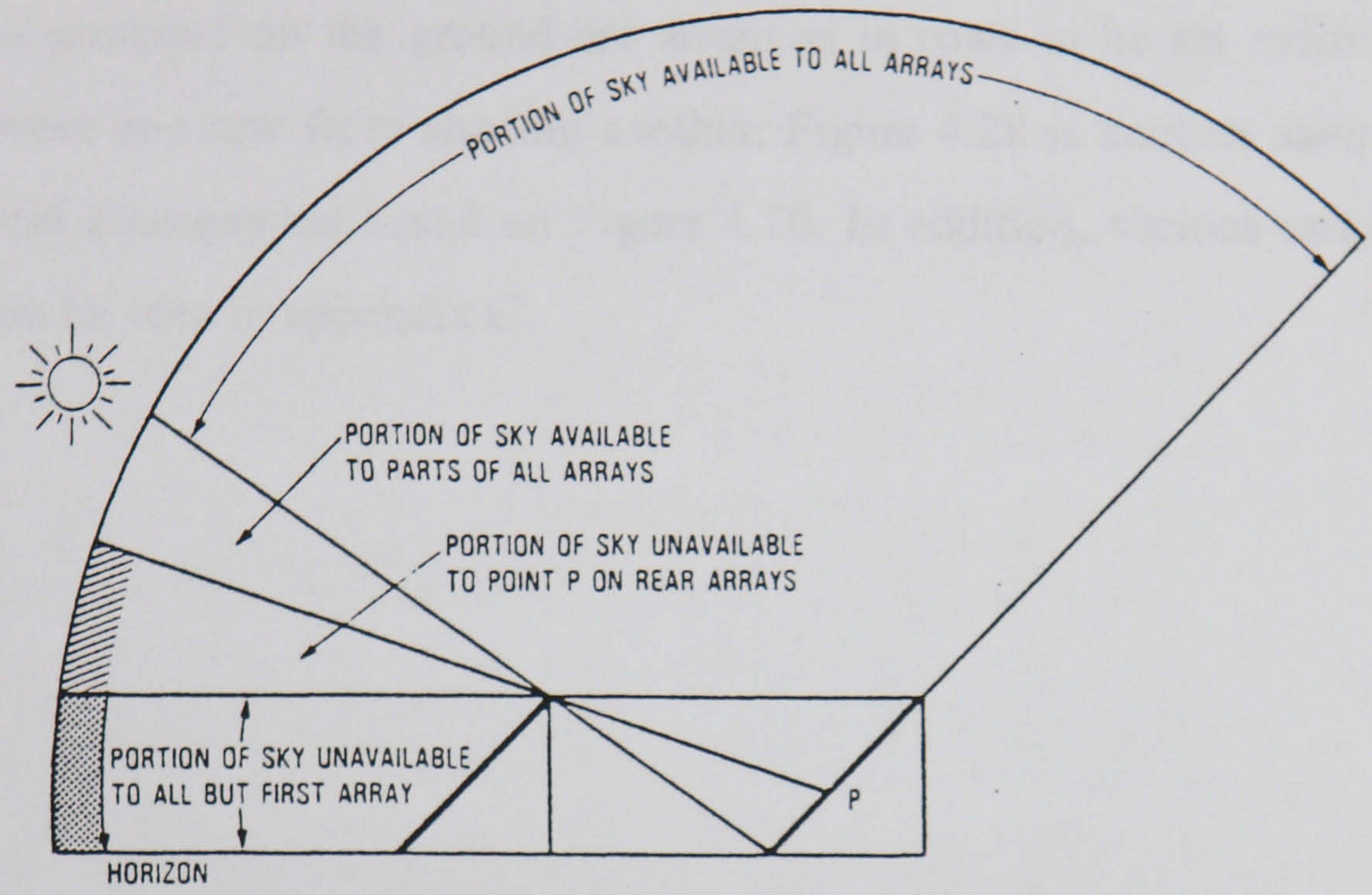


Figure 4.27 Schematic representation of array shadowing from the diffuse radiation component [38]

Another degrading effect apart from the direct shading is the concealing or masking of the diffuse radiation from the panel row in front. This is particularly serious if the distance between the row is small and the climate is such that a large fraction of the total radiation is diffuse. Depending on the position of the sun a panel row can be partly or totally shaded. The effect of shading is a change in the current voltage characteristics of the system and consequently a reduction in output power. Shadowing of the diffuse component of solar radiation is more subtle and easy overlooked, as such shadows are not easily visible to the naked eye. Unlike modeling the direct component shadows, the modeling and diffuse component shadows must account for the anisotropic nature of diffuse lighting and make use of an appropriate sky model for the sky condition being considered. The effect of the diffuse shadowing is similar to the mismatch caused by the shadowing of the direct component except to a lesser degree. Figure 4.27 is a schematic representation of the concept of diffuse shadowing.

4.6.5 Other Designs for PV Array Supporting Structure

The solar array field can be designed on the ground but must be mounted on a solid concrete foundation to prevent high wind from uprooting the array support. The concrete blocks with anchors screwed into the ground will serve this purpose well. Large arrays mounted on the ground are arranged in rows to be set sufficiently far apart to prevent one row from shading another. Figure 4.28 is another sample of the PV array field arrangement based on Figure 4.20. In addition, various array support structures can be seen in appendix C.

Figure 4.28 Another sample of PV array field arrangement based on Figure 4.20

4.7 Design of a Mini-Grid Distribution System

In the case that the PV array is a centralised generator from which electrical power is directly delivered to loads through an electrical power distribution system or mini-grid system in typical villages, distribution systems usually employ such equipment as transformers, circuit breaker and protective devices. The electrical power system in Thailand used for industrial load is three phase, four wires, 380/220 V and 50 H_Z. This power, of course, can be manipulated or changed in many ways with electrical circuitry. Single phase power is generally suitable for lighting and small appliances, for example those used in the home and residential environment. The objective of this topic is to design a mini grid system that will be used within the sample village. The size and type of conductor, protective equipment and grounding of the electrical power distribution system will be calculated. Furthermore, a lightning protection system for direct and indirect strikes will be designed to protect the equipment used in a centralised PV mini-grid system.

4.7.1 Type of Electrical Power Distribution Systems

There are three general classifications of electrical power distribution systems. They are the radial system, the ring or loop system and the network system. Based on typical loads designed for a sample village at Udon Thani Province of Thailand, the radial system is the most suitable for installing in the village. This is because

(i) it is the simplest type compared with the loop and network systems.

(ii) power comes from one power source (PV array generator).

(iii) the system can extend easily to the various areas of a village community.

(iv) it is the least expensive compared to the loop and network systems.

(v) this system is normally used in typical remote areas [39] where other distribution systems are not economically feasible.

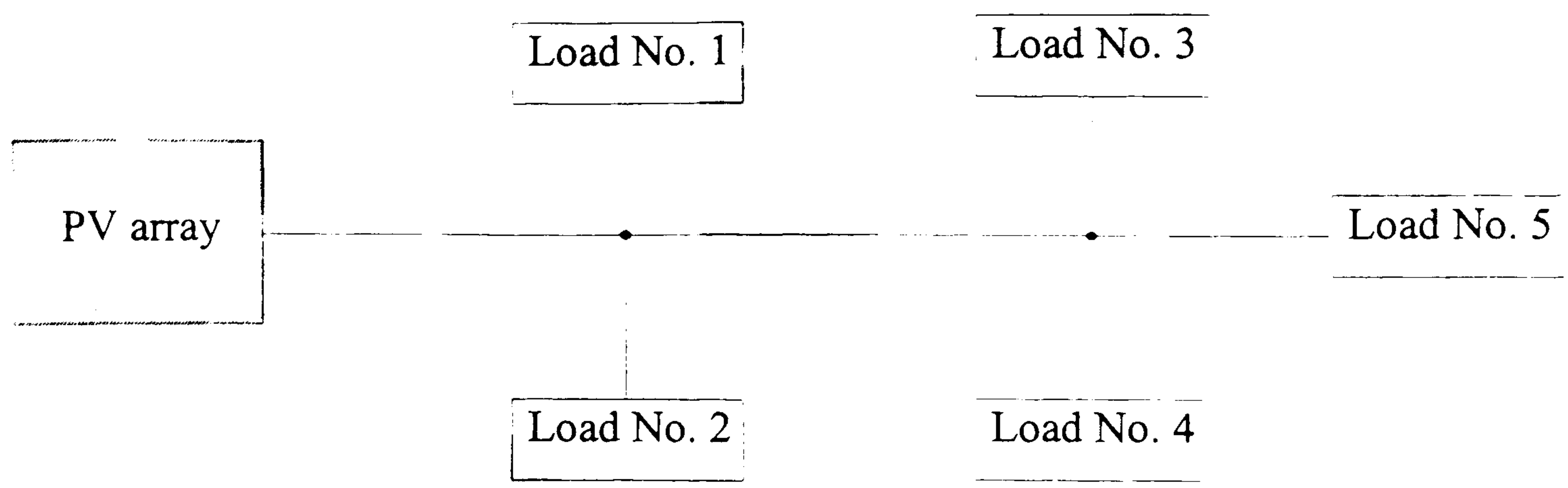


Figure 4.29 A radial power distribution system

In the case of any power line is being opened, one or more loads are interrupted. There is more likelihood of power outages.

4.7.2 Conductor Size of a Mini-Grid System

There are a number of factors in the general design of conductor size. They include percentage of voltage drop in lines, distance between the PV array generator and consumers, and load current that flows through the conductor.

4.7.2.1 Voltage Drop in Electrical Conductors

In the case that the resistance of the conductors is constant, the voltage drop depends on the current that flows through the conductor. Although, the resistance of the electrical conductor is very low, a long length of wire could cause a substantial voltage drop. Remember that a voltage drop is a current multiplied by a resistance accordingly, when the current flows through a conductor, a voltage drop is created. However, a longer section of electrical conductor has a higher resistance. Hence, it is sometimes necessary to limit the length of a conductor. The voltage drop can be calculated from the following equations:

1. DC circuit or single phase with power factor equals unity

$$V_{(drop)} = \frac{2 \times l \times P}{\rho \times A \times V} \tag{4.7}$$

$$V_{(\%)} = \frac{2 \times l \times P \times 100}{\rho \times A \times V^2} \tag{4.8}$$

2. Single phase circuit and power factor is less than unity

$$V_{(drop)} = \frac{2 \times l \times P \times \cos\theta}{\rho \times A \times V} \qquad (4.9)$$

$$V_{(\%)} = \frac{2 \times l \times P \times \cos\theta \times 100}{\rho \times A \times V^2} \qquad (4.10)$$

3. Three phase circuit

$$V_{(drop)} = \frac{\sqrt{3} \times l \times P \times \cos\theta}{\rho \times A \times V} \qquad (4.11)$$

$$V_{(\%)} = \frac{\sqrt{3} \times l \times P \times \cos\theta \times 100}{\rho \times A \times V^2} \qquad (4.12)$$

where

$V_{(drop)}$ = maximum allowable voltage drop (volts)

$V_{(\%)}$ = percent of voltage drop (percent)

l = length of conductor (metres)

A = cross sectional area of conductor (mm^2)

P = electrical power (Watts)

V = supply voltage (volts)

I = current (amperes)

$\cos\theta$ = power factor

ρ = conductivity (Ω.m) for copper $\rho = 65$ and aluminium $\rho = 34$

It is recommended that the maximum allowable voltage drop in a feeder circuit or source circuit does not exceed 5% [40].

4.7.2.2 Determine the Load Current of Each Appliance Used in The Village

In AC circuit, the power factor (PF) of the load should be certainly considered to limit the input current, especially a fluorescent lamp circuit requires an "electromagnetic ballast" to regulate the voltage and current for the lamp operation. A ballast is designed with low PF. Low cost ballasts may suffer from poor PF with approximately 0.2-0.4 for the electromagnetic type and 0.6 for the electronic type. A fluorescent lamp circuit can be improved to a high PF from 0.85 to 0.99 by using a capacitor with a suitable value and which is connected in parallel. For typical industrial loads in

Thailand, the PF is between 0.85 to 0.95. If the value of PF in an industry is low, the current must be higher. In the case of each dwelling and power source supplied from the utility line, the PF of the load is not necessary to improve because electrical power demand is low compared to the industrial loads. However for this project, is being dealt with the centralised PV mini-grid system in the Thai rural village, will recommend how to improve PF with a capacitor for lighting load, especially fluorescent lamp. The input current to supply the lamp can be reduced by this technique

1. Calculation of a Capacitor Value for Power Factor Correction

The smaller static capacitors used in electrical equipment have metal foil plates separated by paper insulation. The capacitors are contained in metal tanks, so that the plates can be immersed in an insulating oil to improve high voltage operation. These units are connected in parallel with power lines to increase the system power factor. A capacitor can be applied in each fluorescent circuit as follows:

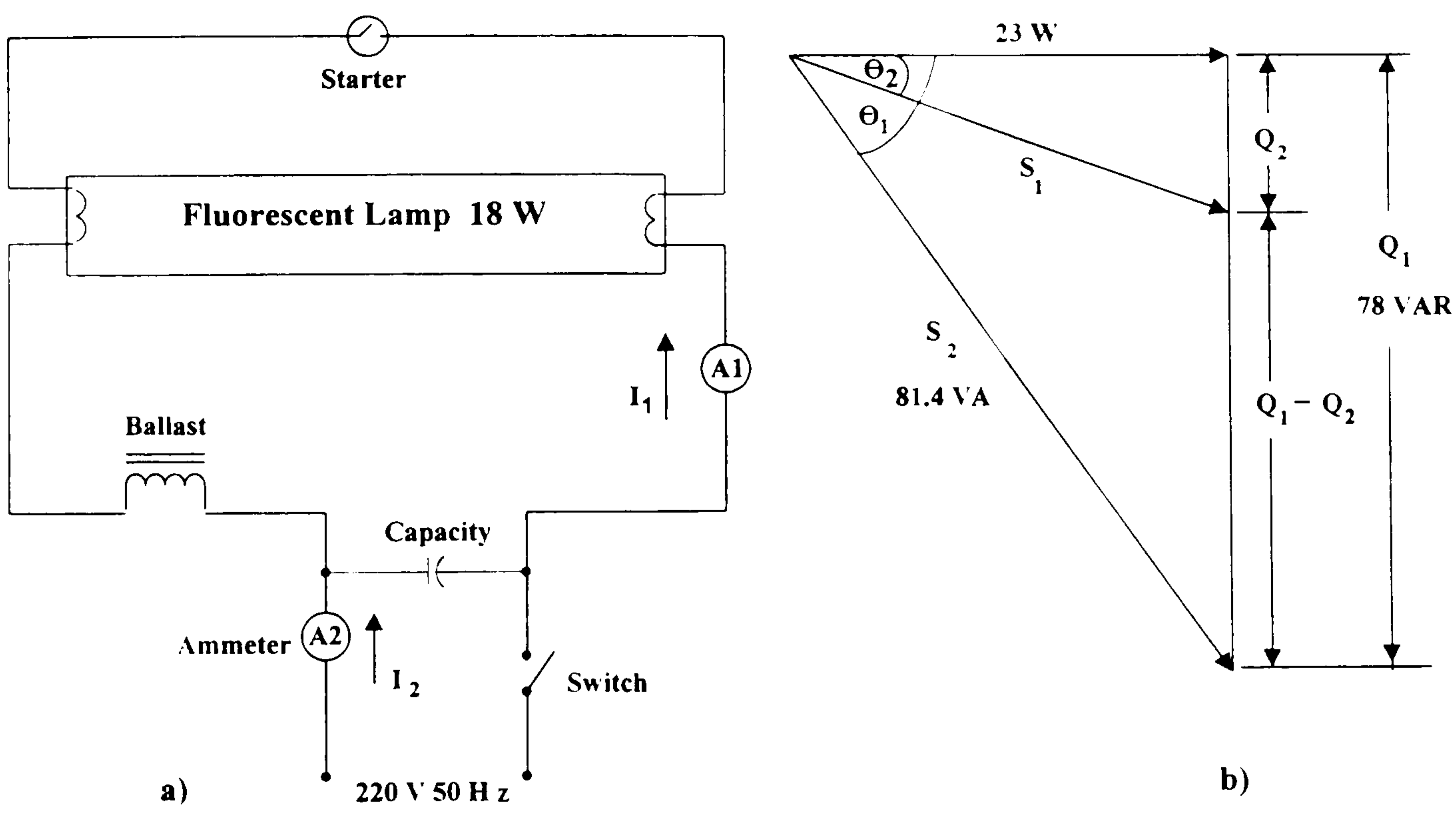


Figure 4.30 a) Circuit of fluorescent lamp with a capacitor to improve PF

b) Vector diagram

In practice, there is a wattage loss in an electromagnetic ballast during operation of approximately 5 watts, and the operating current at 220 V 50 H_z is 0.37 A [41]. It can be measured by an ammeter (A_2). The power factor of the load needs to improve into 0.85 and can be calculated as follows:

Apparent power (S_1) = 0.37×220 = 81.4 Volt-Amp (VA)

True power (P_1) = 18 + 5 = 23 Watts (W)

Reactive power (Q_1) $=\sqrt{S_1^2 - P_1^2} = \sqrt{(81.4)^2 - (23)^2} = 78$ Volt-Amp Reactive (VAR)

$$\cos\theta_1 = \frac{P_1}{S_1} = \frac{23}{81.4} = 0.28, \ \theta_1 = 73.74°$$

$$\cos\theta_2 = 0.85, \ \theta_2 = 31.78°$$

From Figure 4.30b) , yield

$$\text{CVAR} = Q_1 - Q_2 \qquad (4.13)$$

$$= W(\tan\theta_1 - \tan\theta_2) = 23(3.428 - 0.62) = 64.58 \ \text{VAR}$$

(CVAR is the reactive power of the capacity to be used for the PF correction)

The capacitor expressed in μF (micro farad) that is used for PF correction is given by

$$\text{Capacitor(C)} = \frac{\text{kVAR} \times 10^9}{2\pi f V^2} \quad (\mu\text{F}) \qquad (4.14)$$

where f = Frequency in Hertz, use 50 H_Z for Thailand

$$C = \frac{(64.58 \times 10^{-3}) \times 10^9}{2\pi \times 50 \times (220)^2} = 4.2\mu\text{F}$$

If this capacitor is connected in parallel as shown in Figure 4.30 (a), input current will be decreased and can be calculated as follows:

$$S_2 = \frac{P_1}{\cos\theta_2} = \frac{23}{0.85} = 27.06 \ \text{VA}$$

Input current is decreased from 0.37 A to become

$$I_2 = \frac{27.06}{220} = 0.123 \ \text{A at } 220 \text{ V } 50 \text{ H}_Z$$

This current can be read by an ammeter (A_2). Accordingly, it is an easy way to reduce the input current by using a capacitor with 4.2 μF 250 V and connect in parallel with the source for a fluorescent lamp 18 W with an electromagnetic ballast. This is the best way for application in rural areas of Thailand and anywhere. For the circuit of a fluorescent lamp 36 Watts with electromagnetic ballast, which the same method can be used. In practice, the power loss in an electromagnetic ballast will be occur during operation is about 10 Watts and the operating current at 220 V 50 H_Z is 0.44 A [41]. The PF of the load needs to improve to 0.85. A capacitor with 3.72 μF will be needed. As a result, input current is decreased to 0.246 ampere when this capacitor is connected in parallel. The capacitor for both fluorescent lamps 18 W and 36 W should be selected with 4 μF 250 V 50 H_Z (commercially standard capacitor size) to connect in parallel with the AC source of each lamp and in each household.

2 The Load Current for Each Appliance

The load current for each appliance can be determined as follows:

$$I = \frac{P}{V \times PF} \qquad \text{(single phase)} \qquad (4.15)$$

where I = load current (A), P = power (W), V= voltage (V), PF = power factor.

4.7.2.3 Calculation of the Conductor Sizes of a Mini-Grid System in the Sample Village Using a Computer Programme

The voltage drop is a main factor for design of the conductor size of a mini-grid system in the village. It depends on the length of cable or distance between the output inverter and the farthest dwelling including the current flows though it. It is assumed that the site and location plan of a sample village with 100 households is as illustrated in Figures 4.31 and 4.32. This is a sample and based on the radial system of electrical power distribution system. The farthest dwelling in this case is approximately 500 metres from the control building and there are 5 terminal distribution voltage points (b to f). Each point can provide the voltage for up to 20 households. The following design of a mini-grid system in the sample village at Udon Thani province of Thailand is based on a single phase system. This is because the inverter output in the previous design is single phase (see topic 4.4.1.2).

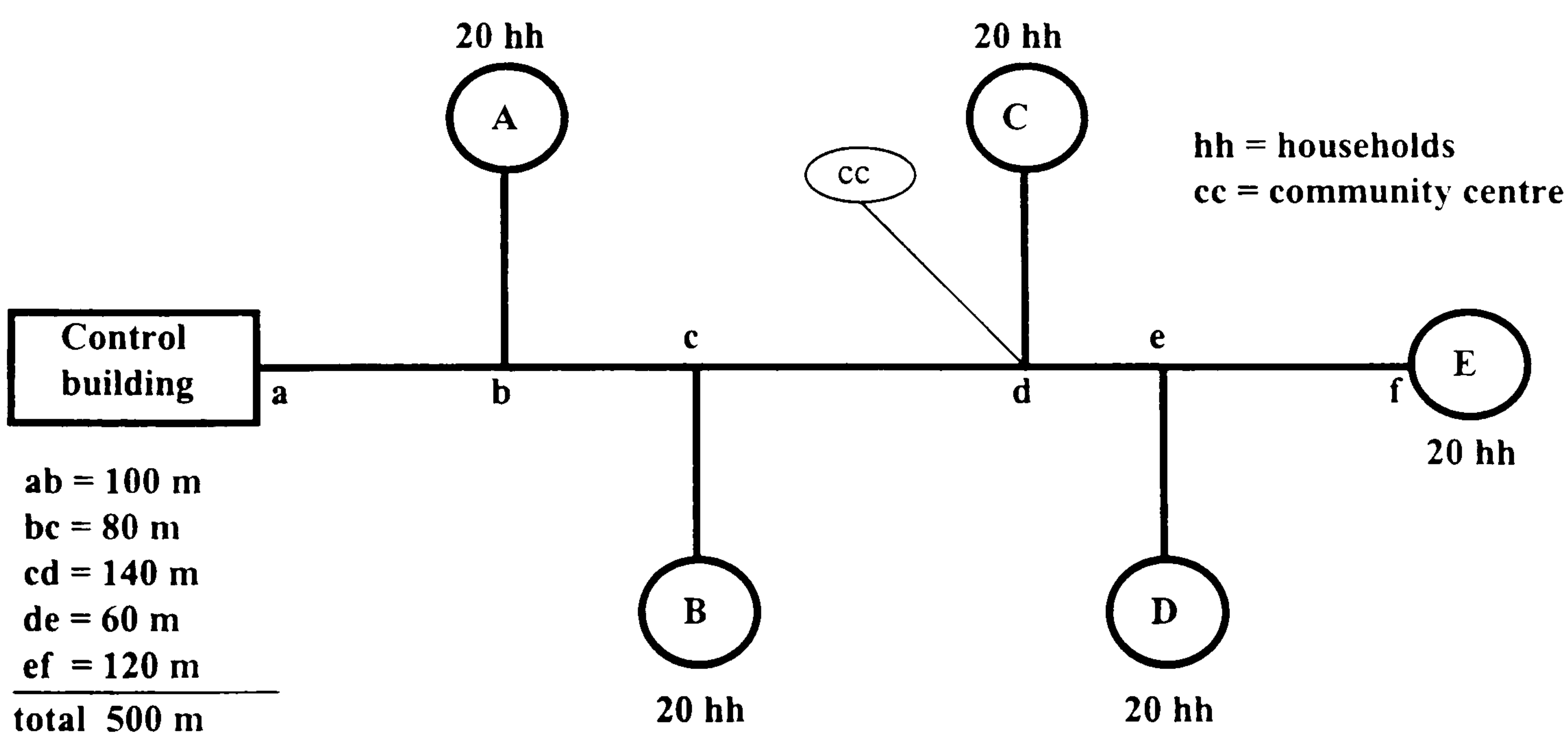
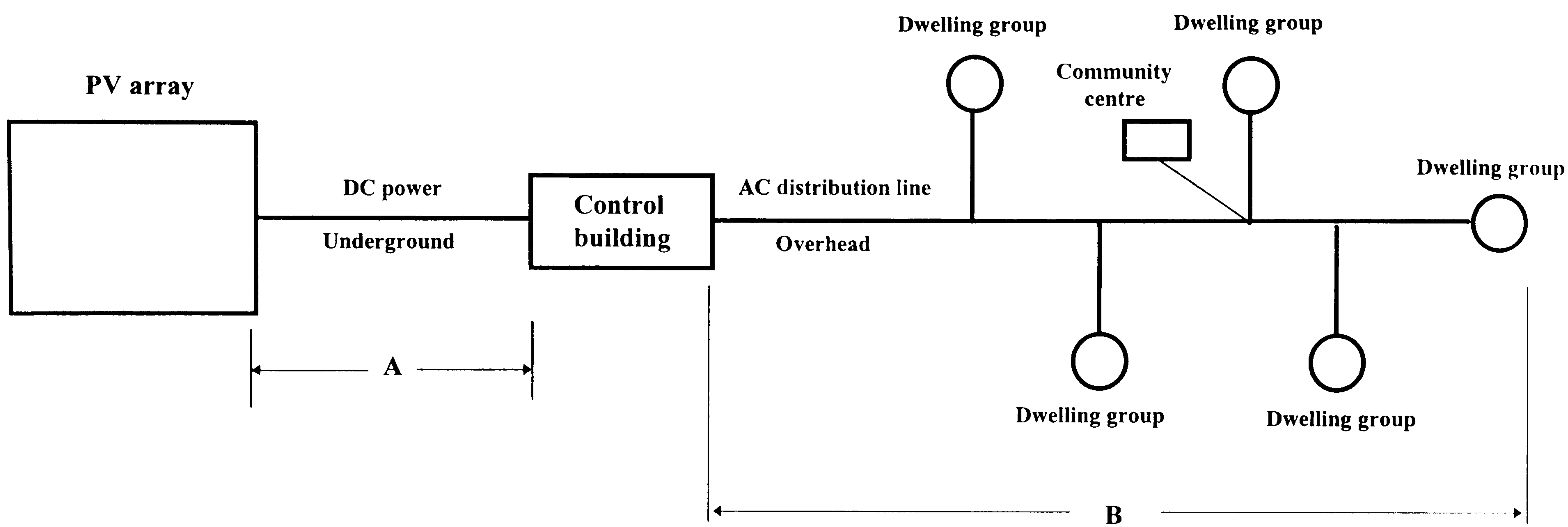


Figure 4.31 Location plan layout of a mini-grid system in the sample village is based on the radial system.



A : Cable length must be kept to a minimum in order to reduce power losses.
For this design the maximum length is 30 metres.

B : Cable length of electrical power distribution system within the sample village.
For this design the maximum length is 500 metres.

Figure 4.32 A sample block diagram of a PV system shows the length of a mini-grid system in the sample village

For the underground system from the solar array to control building, the conductor can be wired in a conduit or can be buried directly. The table below provides useful data to find the maximum number of cables that can be inserted in a conduit.

Table 4.10 Maximum number of cables in a conduit [42].

Cable size	Commercial standard size of conduits - mm (inch)											
(mm^2)	15 (1/2)	20 (3/4)	25 (1)	35 (1 ¼)	40 (1 ½)	55 (2)	65 (2 ½)	80 (3)	90 (3 ½)	100 (4)	115 (4 ½)	130 (5)
0.5	17	*	*	*	*	*	*	*	*	*	*	*
1	13	*	*	*	*	*	*	*	*	*	*	*
1.5	11	19	*	*	*	*	*	*	*	*	*	*
2.5	7	13	22	*	*	*	*	*	*	*	*	*
4	5	10	16	*	*	*	*	*	*	*	*	*
6	3	6	11	19	25	*	*	*	*	*	*	*
10	1	4	7	12	16	*	*	*	*	*	*	*
16	1	3	5	8	11	19	*	*	*	*	*	*
25	1	1	3	5	7	12	18	*	*	*	*	*
35	1	1	2	4	6	10	14	22	*	*	*	*
50	*	1	1	3	4	7	10	15	20	*	*	*
70	*	1	1	1	3	5	8	12	16	20	*	*
95	*	*	1	1	1	4	6	9	12	15	19	*
120	*	*	1	1	1	3	5	7	10	13	16	20
150	*	*	*	1	1	2	4	6	8	10	13	16

Based on Figures 4.31 and 4.32, the conductor sizes of a mini-grid system from the control building to each household and the underground system from the PV array to the control building can be determined using a computer programme. The flow diagram of this programme can be found in appendix B.

The Input Data and the Results of a Computer Programme

: description of data :

no. of households in a village = 100.0 households
type of system = 1.0 phase
nominal system voltage (AC side) = 220.0 VAC
power factor = 0.85
lighting load for each household = 8.0 W quantity = 100.0
lighting load for community centre and battery room = 18.0 W quantity = 100.0
street lighting load = 26.0 W quantity = 20.0
radio load = 10.0 W quantity = 100.0
TV load = 120.0 W quantity = 1.0
video load = 40.0 W quantity = 1.0
refrigerator load = 320.0 W quantity = 1.0
other loads = 0.0 W quantity = 0.0
pumping load at night time (if any) = 0.0 W quantity = 0.0
power loss in ballast/lamp for F. lamp (8.0 W) = 3.0 W
power loss in ballast/lamp for F. lamp (18.0 W) = 5.0 W
power loss in ballast/lamp for F. lamp (36.0 W) = 10.0 W
power loss in ballast/lamp for street lighting lamp (26.0 W) = 9.0 W

: details of total load current of each appliance (100.0 households) :

current of radio load = 5.35 A
current of fluorescent lamp (8.0 W) = 5.88 A
current of fluorescent lamp (18.0 W) = 12.30 A
current of fluorescent lamp (36.0 W) = 2.46 A
current of street lighting load = 3.74 A
current of TV load = 0.64 A
current of video load = 0.21 A
current of refrigerator load = 1.71 A
current of other loads = 0.00 A
total current = 32.30 A
power factor = 0.85
nominal system voltage of load = 220.0 VAC

: mini-grid distribution system within the sample village (overhead line) :

cable length from control room housing to farthest load = 500.0 metres
maximum allowable percentage of voltage drop = 2.0 %
type of electrical power distribution system = 1.0 phase 220.0 VAC
conductor size (hot line) = 120.0 mm2
conductor type = THW
actual percentage of voltage drop in cable = 1.9 %
power loss = 133.8 W
cable efficiency = 99.1 %

: Electrical power distribution line (underground system) :

cable length from PV array to control room housing = 30.0 metres
maximum allowable percentage of voltage drop = 2.0 %
maximum current flows through the cable = 75.5 ADC
maximum voltage that PV array can generate = 270.0 VDC

: In the case of cable must be buried in the ground with a conduit :

conductor size = 35.0 mm2
actual percentage of voltage drop = 0.7 %
maximum power loss = 89.7 W
cable efficiency = 99.6 %
conductor type = THW
no. of cable in conduit = 2.0
diameter of conduit = 1.00 inches
minimum depth of burying = 45.0 cm.

4.8 Lightning Protection System

Lightning strokes are the visible discharge of static electricity accumulated in storm clouds created by weather condition. Strokes may occur within the clouds, between clouds, or from the cloud base to earth. Lightning is formed as a result of a natural build-up of electrical charge separation in storm clouds. The base of a storm cloud is approximately 5-10 km above the earth's surface, with the cloud 12 km high. The charge at the base of the cloud is usually negative and induces an equal and opposite charge on the earth's surface and earth objects beneath the cloud. In the simplest form the lighting stroke is comprised of a leader and return stroke. The leader progresses from cloud to ground in a series of jerks or steps between which there is a pause of 30-100 μS [43]. The fast rise time and large peak amplitude of the stroke can provide severe mechanical effects. Long duration current can cause fire, while short duration high current peaks tend to tear or bend metal parts when they make contact. A typical current amplitude against time waveform is shown in Figure 4.33 [44].

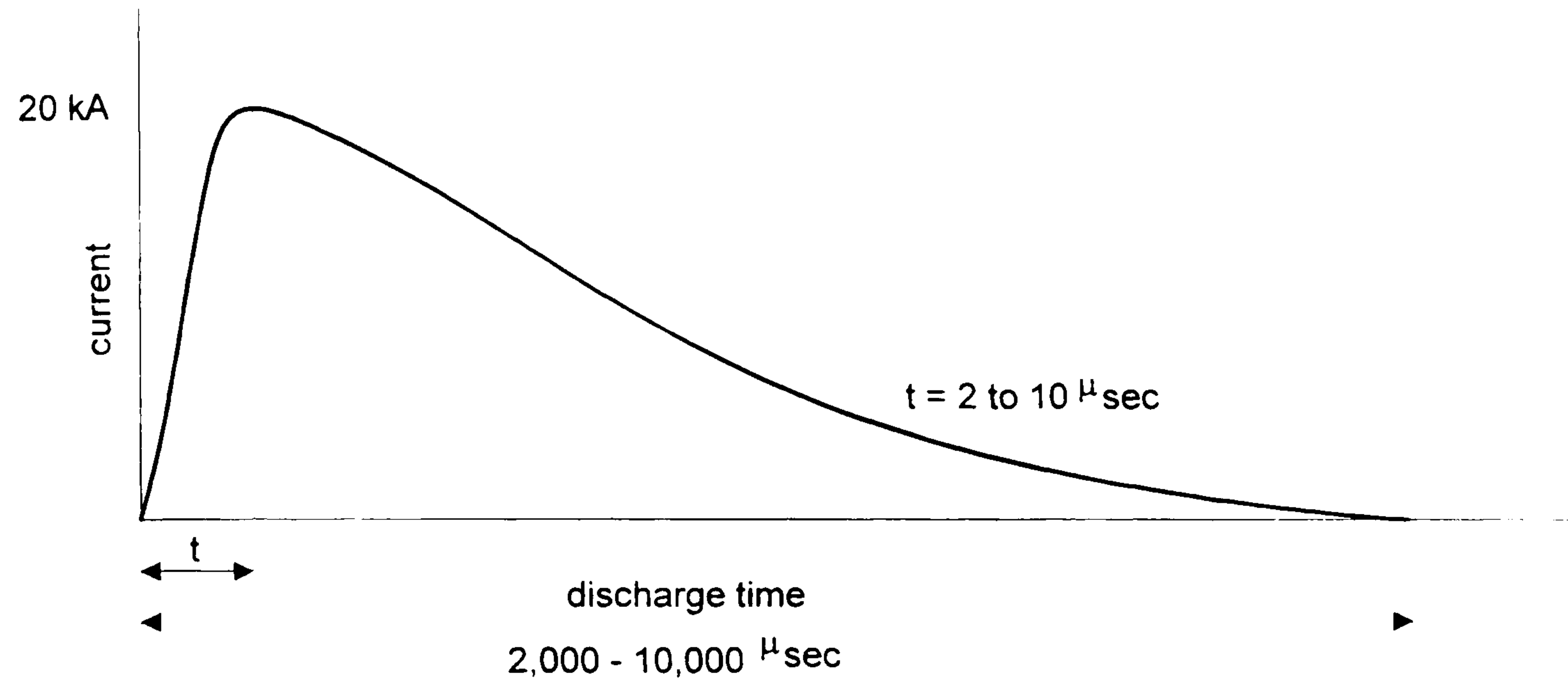


Figure 4.33 Current amplitude against discharge time of a typical lightning stroke

The current amplitudes can range from several kA up to 200 kA. Fortunately super bolts of 100 kA are rare the statistical average was recorded at 20 kA. The core of the discharge may reach a temperature of 30,000 K causing explosive expansion of the air and the typical sound of thunder.

4.8.1 Effect on Electrical Power Distribution System

The overhead distribution system or a mini-grid system can be affected by lightning in two ways, namely by direct stroke and by the over-voltage induced (called indirect stroke) by near misses. When a lighting stroke falls near to an overhead line, a voltage is induced in that line. There is the local partial collapse of the field between earth and the cloud, E, typically 50 kV/m [44] which enables bound charges in the line to be released so raising the potential of the line to a value approaching E×L, where L is the height in metres of the line. Furthermore, close lightning strokes will induce high voltage in a PV array and in the grounding structure. These voltages may damage the power conditioner or other equipment. For grid connected PV systems the utility grid and connected loads may also be affected by this induced voltage. A typical close lightning stroke will induce a voltage of approximately 0.3 V/kA per module based on a lightning stroke at a distance of 0.8 metre and with a current discharge of 3 kA per μS [45]. For strings, the total induced voltage can be approximately estimated by the sum of the induced voltage per module.

4.8.2 The Need for Protection

A centralised PV array installed in a high risk environment will require the highest possible class of lightning protection. The British Standard (BS 6651) provides a simple procedure for overall risk factor analysis for assessing whether a structure needs protection. It suggests that an acceptable lightning stroke risk factor is 10^{-5}per year, that is 1 in 100,000 per year. Therefore, having applied the mathematical analysis to a particular set of parameters, the PV designers will achieve a numerical solution. If the risk factor is less than 10^{-5} (1 in 100,000) then, without other over riding considerations, protection is deemed unnecessary. However, the risk factor is greater than 10^{-5}, then the protection would seem necessary. The factors that should be considered for determining an overall risk factor can be summarized as follows:

4.8.2.1 The Geographical Location of the Structure

This pinpoints the average lightning flash density or the number of flashes to ground per km^2 per year. For structures sited within Thailand these figures can be taken from the map as shown in Figure 4.34 and are also included in Table 4.11.

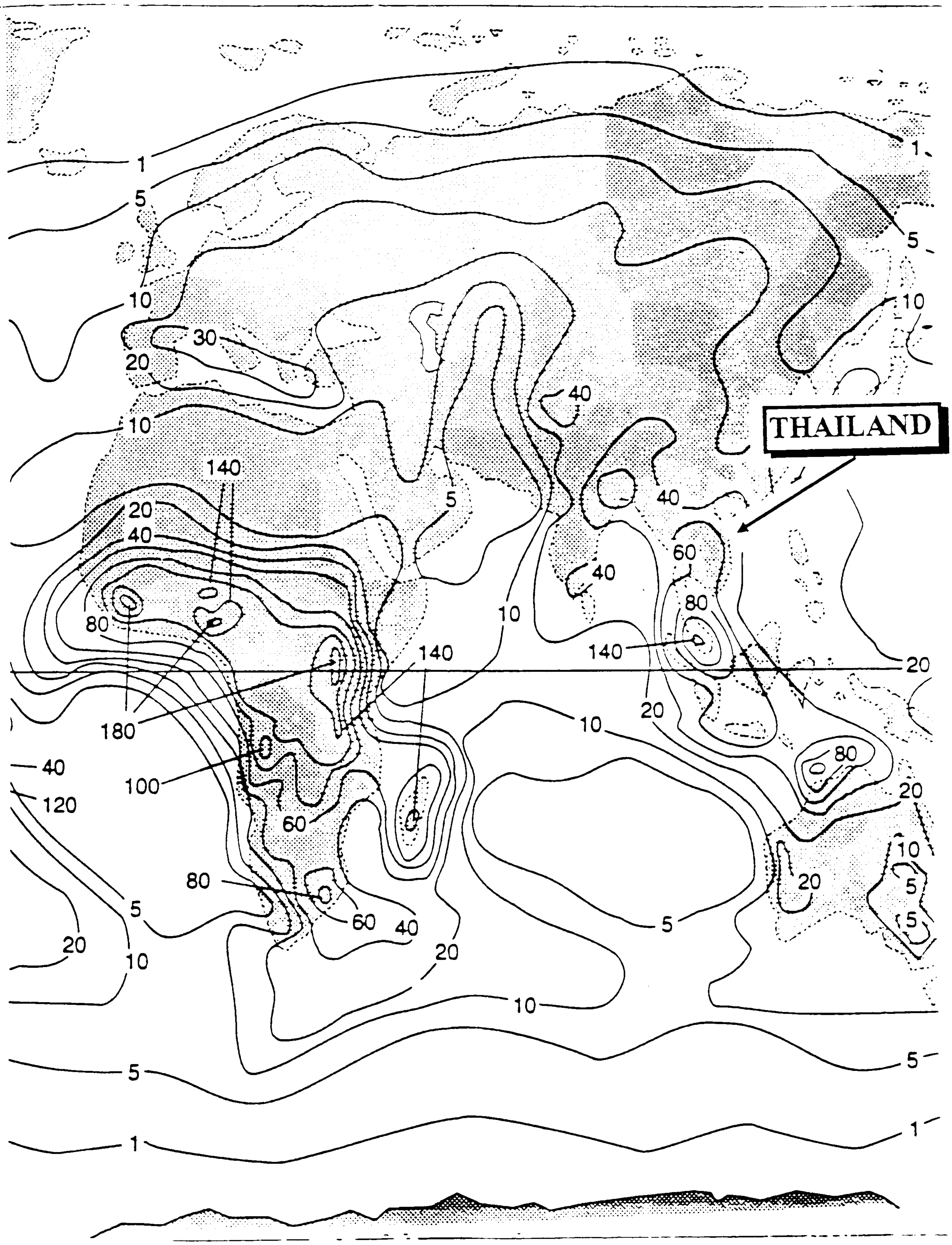


Figure 4.34 Map showing thunderstorm days throughout around Thailand is based on information from the world Meteorological Organization records for 1955 [46].

Table 4.11 Relationship between thunderstorm days per year and lightning flashes/km^2/year.

Thunderstorm days per year	Flashes/km^2/year (N_g)	
	Mean	Limits
5	0.2	0.1 to 0.5
10	0.5	0.15 to 1
20	1.1	0.3 to 3
30	1.9	0.6 to 5
40	2.8	0.8 to 8
50	3.7	1.2 to 10
60	4.7	1.8 to 12
80	6.9	3 to 17
100	9.2	4 to 20

4.8.2.2 The Effective Collection Area of the Structure

This is the plan area, projected in all directions taking account of the structure's height. The significance is that the larger the structure, the more likely it is to be struck (see Figure 4.35).

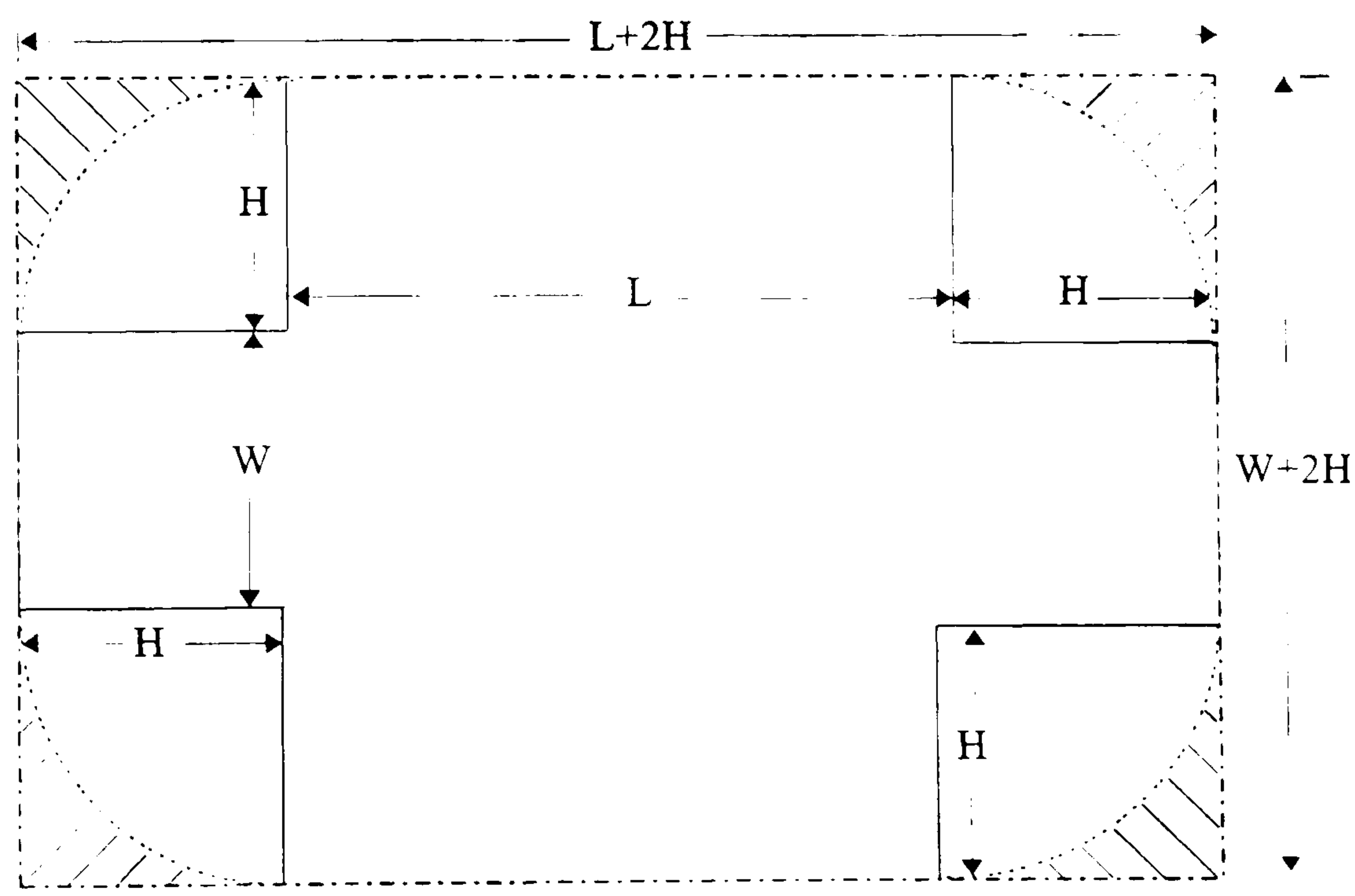


Figure 4.35 Effective area of a structure length (L), width (W) and height (H).

For a simple rectangular box shaped structure as shown in the figure above, the effective area (symbol A_e) is simply the product of the following equation.

$$\begin{aligned} A_e &= LW + 2HW + 2HL + \pi H^2 \\ &= (L + 2H)(W + 2H) - (4 - \pi)H^2 \\ &= (L + 2H)(W + 2H) - 0.86H^2 \end{aligned} \tag{4.16}$$

where L = length, W = width and H = height.

The height plays the largest part in the calculation of the effective area. The probable number of strikes to the structure is the product of lightning flash density (N_g-see Table 4.11) and the effective area (A_e) is calculated from the above equation.

Table 4.12 Weighting factors A, B, C, D and E (from BS 6651 : 1992)

Weighting factor A (use of structure)	Value of factor A	Weighting factor B (type of construction)	Value of factor B
Houses and other Buildings of comparable size	0.3	(1) Steel framed encased with any roof other than metal	0.2
Houses and other buildings of comparable size with outside aerial	0.7	Reinforced concrete with any roof other than metal	0.4
Factories, workshops and laboratories	1.0	Steel frame encased or reinforced concrete with metal roof	0.8
Office blocks, hotels, blocks of flats and other residential buildings other than those included below	1.2	Brick, plain concrete or masonry with any roof other than metal or thatch	1.0
Places of assembly, eg churches, halls, theatres, museums, exhibitions,	1.3	Timer framed or clad with any roof other than metal or thatch	1.4
department stores, post offices, stations, airports and stadium structures		Brick, plain concrete, masonry, timber framed but with metal roofing	1.7
Schools, hospitals, children's or other homes	1.7	Any building with a thatched roof	2.0

Weighting factor C (contents or consequential effects)	Value of factor C	Weighting factor D (degree of isolation)	Value of factor D
Ordinary domestic or office buildings, factories and workshops not containing valuable or specially susceptible contents	0.3	Structure located in a large area of structures or trees of the same or greater height, eg in a large town or forest	0.4
(2) Industrial and agricultural buildings with specially susceptible contents	0.8	Structure located in an area with few other structures or trees of similar height	1.0
Power stations, gas installations, telephone exchanges and radio stations	1.0	Structure completely isolated or exceeding at least twice the height of surrounding structure or trees	2.0
Key industrial plants, ancient monuments and historic buildings, museums, art galleries or other buildings with specially valuable contents	1.3		
School, hospital, children's and other homes, places of assembly	1.7		

Weighting factor E (type of country)	Value of factor E
Flat country at any level	0.3
Hill country	1.0
Mountain country between 300 m and 900 m	1.3
Mountain country above 900 m	1.7

(1) *A structure of exposed metal which is continuous down to ground level is excluded from the table as it requires no lightning protection beyond adequate earthing arrangements.*

2) *This means specially valuable plant or materials vulnerable to fire or the results of a fire.*

4.8.2.3 The Overall Risk Factor (ORF)

The calculation of how a particular structure is affected involves a weighting factor based on 5 other factors. Thus the overall weighting factor (W) is given by:

$$W = A \times B \times C \times D \times E \qquad (4.17)$$

The overall risk factor (ORF) is

$$ORF = W \times N_g \times A_e \times 10^{-6} \qquad (4.18)$$

It is considered that if ORF is less than 10^{-5} the risk is acceptable.

$$W \times N_g \times A_e \times 10^{-6} < 10^{-5}$$

The following example is for a centralised PV array in the sample village at Udon Thani province of Thailand, based on previously designed.

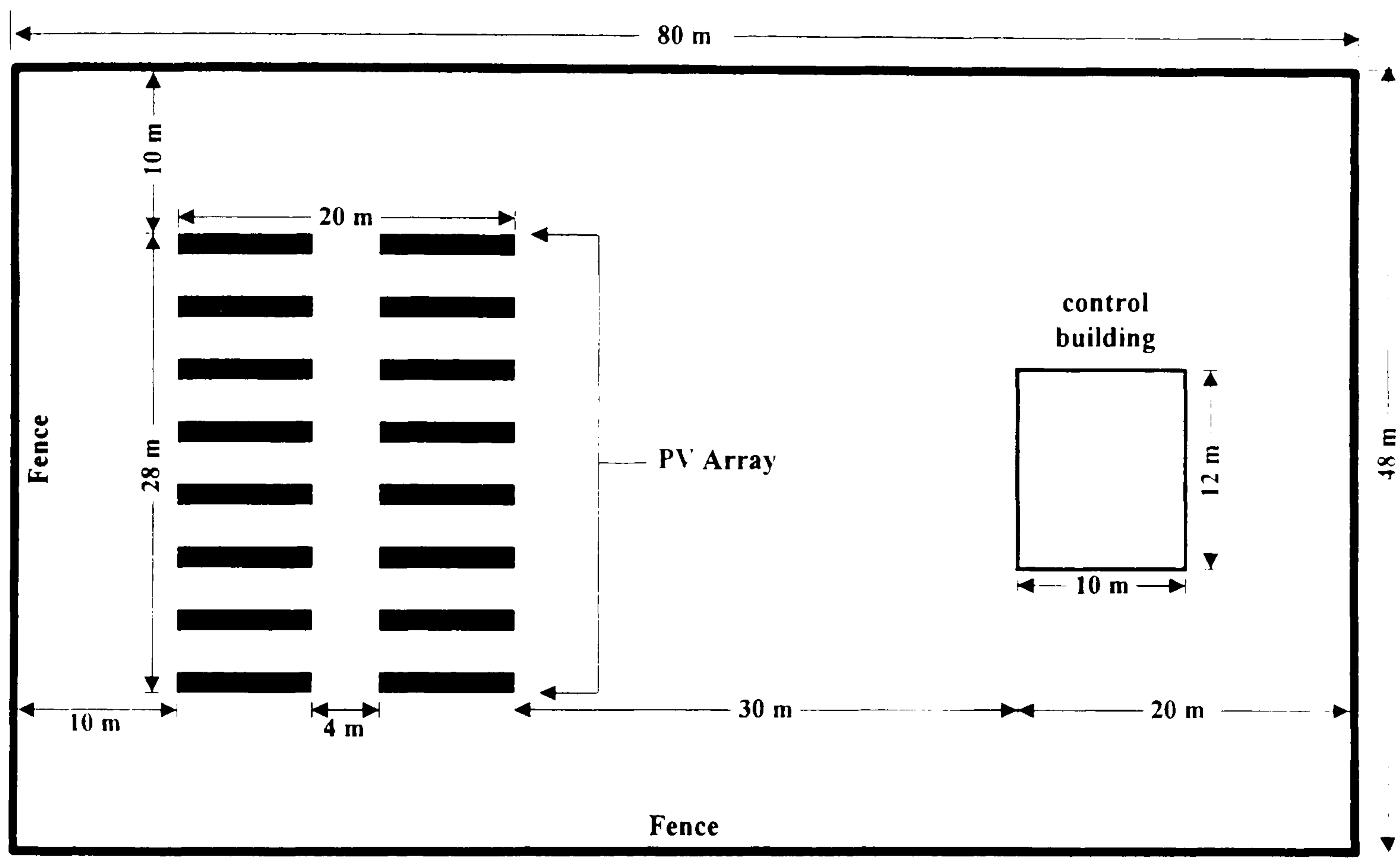


Figure 4.36 Layout site and location of PV array field

For a control building (housing), the electrical and electronic equipment is particularly vulnerable to lightning because of the induced effects of lightning on main's supplies and on data cables. This means that lighting strike some distance from a building can affect electronic equipment within the building. The British Standard (BS 6651) provides a risk assessment for the electronic equipment within a building, which is similar to the risk assessment for the structure alone. The main difference is that the effective area of collection is calculated differently as follows:

- The plan area of the structure.
- The collection area of the surrounding ground, this is a distance D in metres from the perimeter of the structure, where D is numerically the resistivity of the soil up to a minimum of 500. However, if the height of the structure exceeds D calculated in this way, then the collection area D is assumed equal to the height.
- Effective collection area of incoming main services.

Table 4.13 Effective collection area of mains service

Type of mains service	Effective collection area
Low voltage overhead cable	$10 \times D \times L$
High voltage overhead cable (to on-site transformer)	$4 \times D \times L$
Low voltage under ground cable	$2 \times D \times L$
High voltage underground cable (to on-site transformer)	$0.1 \times D \times L$

Note: D is the collection distance in metres. L is the length in metres of power cable with a maximum value of 1000 m. Where the value of L is unknown a value of 1000 m should be used.

- Effective collection area of data lines leaving the earth reference of the building. The data lines have to be electric to count, i.e., fiber optic cable has zero area

Table 4.14 Effective collection area of data line

Type of data line	Effective collection area
Overhead signal line	$10 \times D \times L$
Underground signal line	$2 \times D \times L$
Fiber optic cable without a conductive metallic shield or core	0

Note: D is the collection distance in metres. L is the length in metres of power cable with a maximum value of 1000 m. Where the value of L is unknown a value of 1000 m should be used.

The overall risk of a strike that will affect electrical or electronic equipment depends on the parameters in the table below.

Table 4.15 Weighting factors F, G and H

Weighting factor F (type of construction)	
Type of structure	value of F
Buildings with lightning protection and potential bonding to BS 6651	1
Buildings with lightning protection and potential bonding to CP 326	1.2
Building where equip-potential bonding for electrical or electronic equipment reference may be difficult (e.g. buildings over 100 m long)	2.0
Weighting factor G (degree of isolation) (= D)	
Degree of isolation	value of G
Structure located in a large area of structures or trees of the same or greater height, e.g. in a large town or forest	0.4
structure located in an area with few other structures or trees of similar height	1.0
Structure completely isolated or exceeding at least twice the height of surrounding structure or trees	2.0
Weighting factor H (type of terrain) (= E)	
Type of terrain	value of H
Flat country at any level	0.3
Hill country	1.0
Mountain country between 300 m and 900 m	1.3
Mountain country above 900 m	1.7

The overall risk (R) of a lightning induced transient overvoltage is

$$R = F \times G \times H \times P$$

where P is the probable number of flashes for the area A_e, its value is

$$P = A_e \times N_g \times 10^{-6} \text{ flashes/year}$$

Finally, having calculated R, Table 4.16 gives the consequential loss rating of damage to contents.

Table 4.16 Classification of structure and contents

Structure used and consequential effect of charge to content	Consequential loss rating
domestic dwelling and structure with electronic equipment of low value and small cost penalty due to loss of operation	1
Commercial or industrial buildings with essential computer data or computer processing where equipment damage and downtime could cause significant disruption	2
Commercial or industrial applications where loss of data or computer process control could have severe financial costs	3
Highly critical processes where loss of plant control or computer operation may lead to severe environmental or human cost (i.e. nuclear plant, chemical work etc.)	4

Table 4.17 Classification of exposure level

Consequential loss rating	Exposure level			
	R < 0.005	R = 0.005 to 0.0499	R = 0.05 to 0.499	R > 0.5
1	Negligible	Negligible	Low	Medium
2	Negligible	Low	Medium	High
3	Low	Medium	High	High
4	Medium	High	High	High

Note : Exposure level categories in previous table are based on a lightning risk assessment only. If transients of other origin are present, consideration should be given to upgrading protectors, e.g. if in an industrial area the risk assessment suggests a surge protection device suitable for a medium exposure level is appropriate, the presence of inductive switching transients may make a high exposure level device appropriate, In these circumstances, specialist/manufacturer's advice should be sought.

The table above gives ranges of R against consequential loss rating. It is possible to classify the exposure level as negligible, low, medium and high, for which only the negligible class requires no protection. The control building will be protected to BS 6651, when N_g = 4.7 flashes/km^2/year. The sample control building at Udon Thani province has an earth resistance of 100 Ω-m with 30 m of low voltage with underground cable for the mains service, and the 30 m data line is electrically conducting. If the consequential loss rating of the electronic equipment was deemed to be two, then a surge protection device should be fitted suitable for a medium exposure level.

4.8.3 Components of Lightning Protection System

The main component of a lightning protection system is composed of the following: (i) air termination, (ii) down conductor (iii) earth termination, (iv) joint and bonds. In practice, it is essential that the resistance to earth is lowest down the lighting conductor than for other routes. The whole earth termination network should have a combined resistance to earth not exceeding 10 ohms without taking into consideration any bonding to other services.

4.8.3.1 Air Termination Network

The simplest form of air termination is the air rod. BS 6651 introduces the idea of air termination networks on all sides of tall buildings. No part of the roof within the air termination network should be more than 5 m from a conductor. For large flat roofs this will be achieved typically by a network mesh of 10 m × 20 m. For a high risk structure, the air termination mesh is reduced to 5 m × 10 m.

4.8.3.2 Down Conductor

The main function of a down conductor is to provide a low impedance path from the air termination network to the earth termination network, to allow the lightning current to be safely conducted to earth. Sharp bends in down conductors at the edge of the roofs are unavoidable and are permitted in BS 6651, however, re-entrant loops in a conductor can produce high inductive voltage drops which could lead to the lightning discharge jumping across the side of the loop. To minimise this problem, BS 6651 recommends that the length of the conductor forming the loop should not exceed eight times the width of the open side of the loop. Each external down conductor must incorporate a test clamp installed approximately 3 metres from ground level. This enables the continuity of the system to be checked as well as isolating each local earth network for testing purposes.

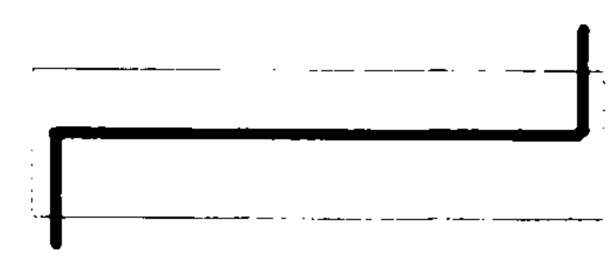
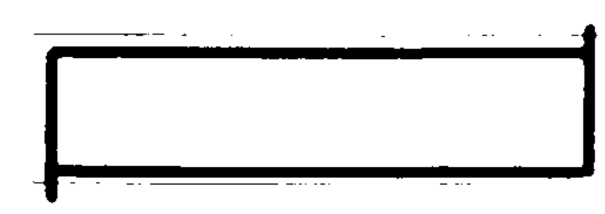
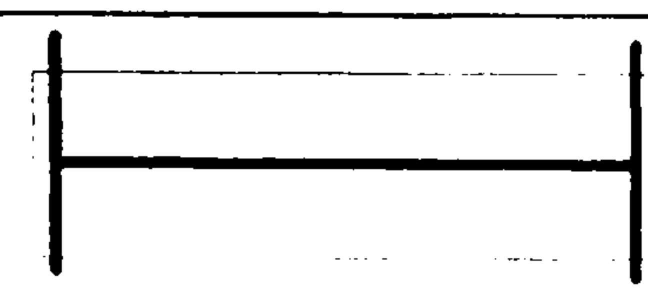
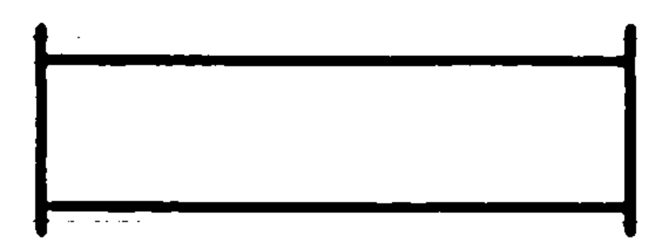
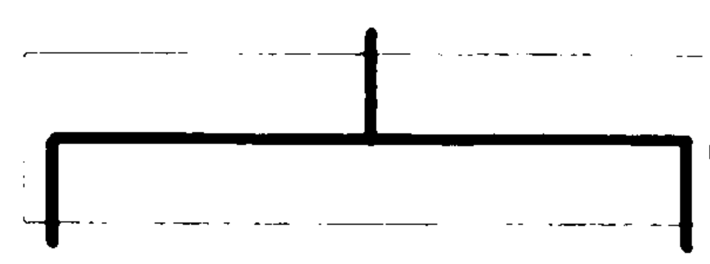
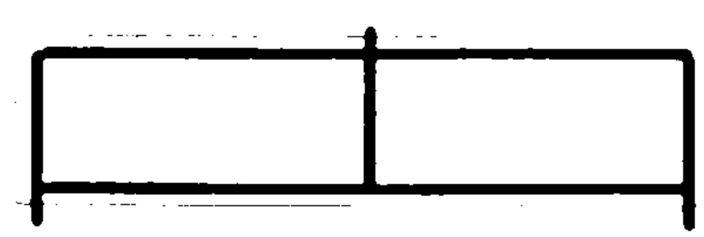
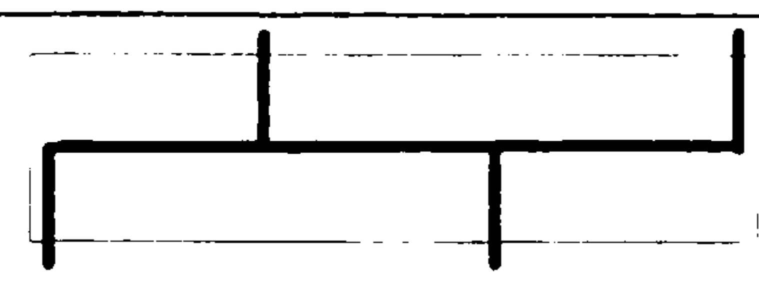
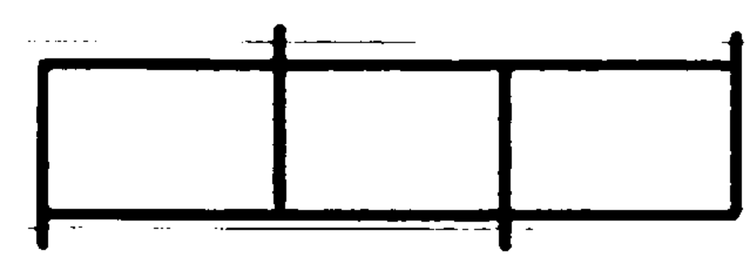
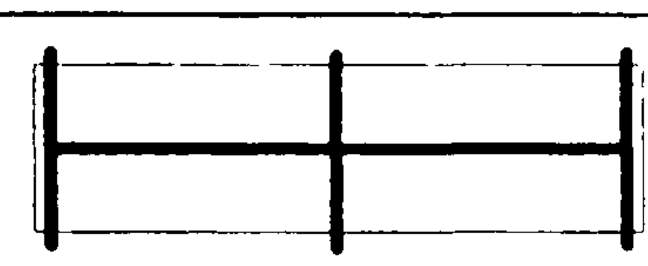
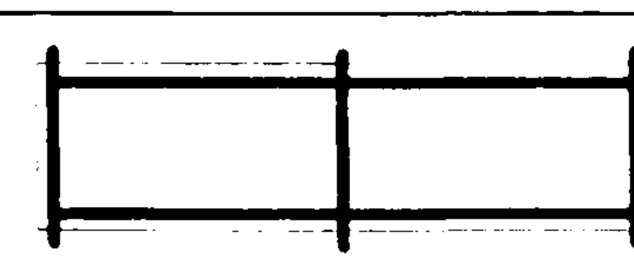
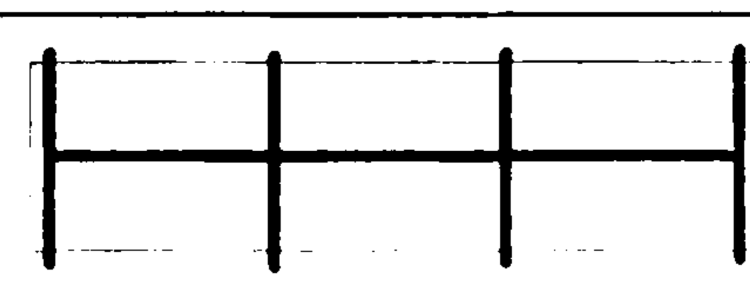
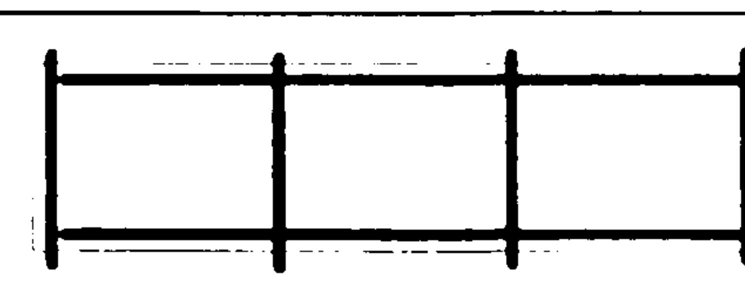
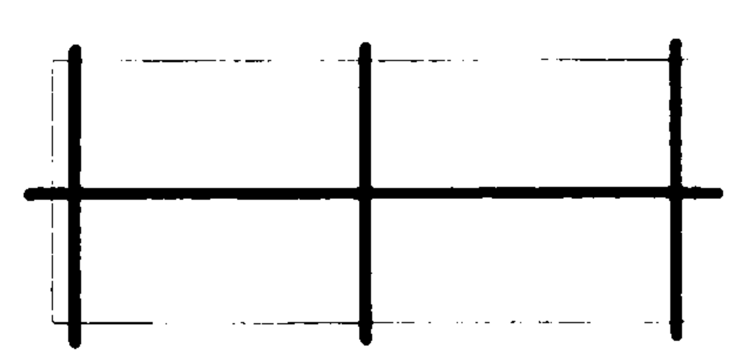
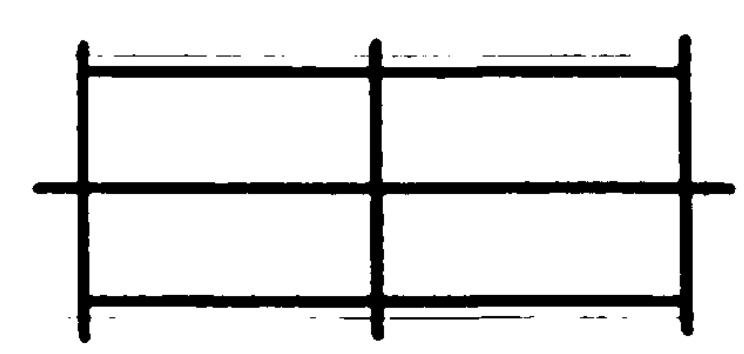
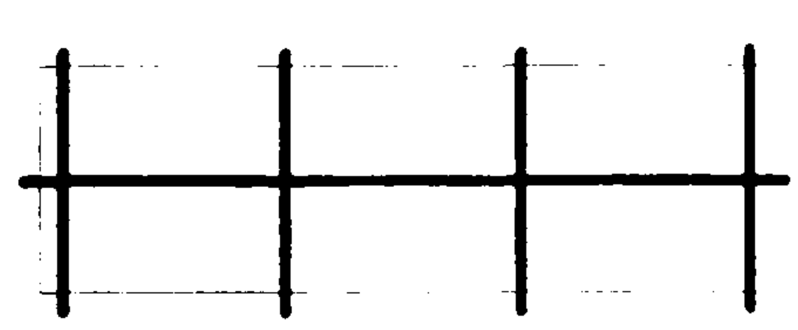
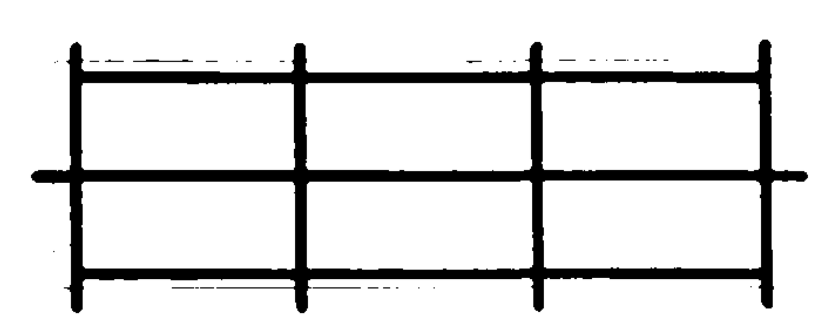
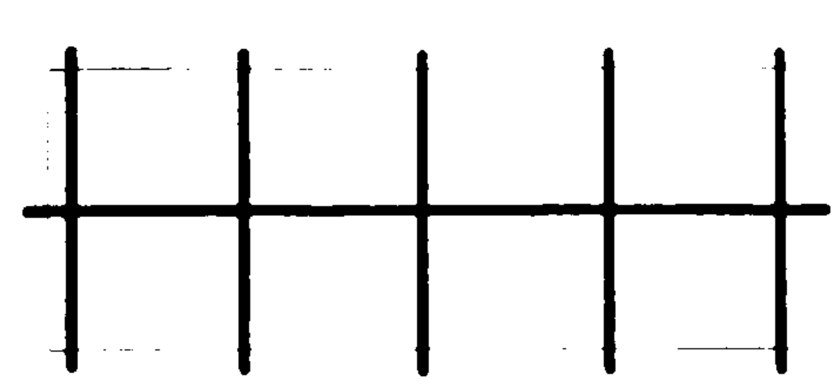
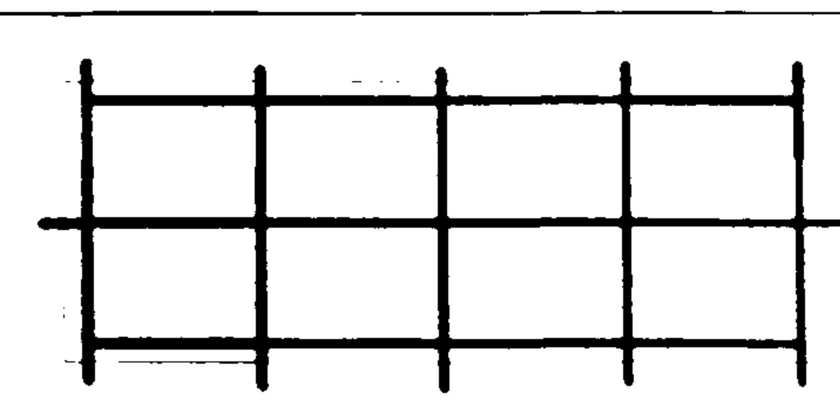
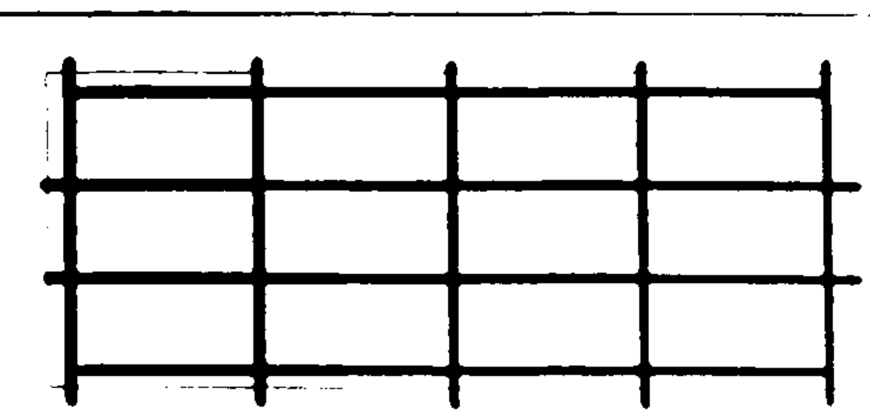
4.8.3.3 Earth Termination Network

The two metals commonly used in lightning protection system are aluminium and copper. If aluminium is selected as the material for air termination networks and down conductors, it has to be converted to copper at or around the test clamp. This is because both BS 6651 and the Earthing Code BS CP 1013 do not permit aluminium to be buried underground due to the likelihood of corrosion. An effective means of joining the aluminium and copper conductor is with a friction welded bi-metal clamp. If they are used in conjunction with an inhibitor grease, thus minimizes the effect of corrosion. There are two stages in testing an earth network for satisfactory resistance as follows:

- with the test link removed from the down conductor and without any bonding to other services, the earth resistance of each earth electrode should be measured. The resistance (in ohms) should not exceed ten times the number of down conductors on the structure. If there are fifteen down conductors equally spaced around a building, then the resistance of each electrode with test link removed should not exceed 10 × 15 = 150 ohms.

- with the test links replaced, the resistance to earth of the complete lightning protection system is measured at any point on the system. The reading from this test should not exceed 10 ohms.

Table 4.18 Configuration arrangement of air terminal and down conductor [47]

Building (m)		Number of conductors	Configuration of down conductor arrangement	
length	width		slope roof	flat roof
to 20	to 12	2		
to 20	12-20	4		
20-40	to 12	3		
40-60	to 12	4		
20-40	12-20	6		
40-60	12-20	8		
20-40	20-40	8		
40-60	20-40	10		
60-80	20-40	12		
60-80	40-60	14	---	

4.8.3.4 Bonds

All metalwork on or around a structure must be bonded to the lightning protection system if side-flashing is to be avoided. In practice, water pipes, gas pipes, metal sheaths and electrical installations that are in contact with earth, remain at earth potential during a lightning discharge. There are two ways of preventing side-flashing. To isolate nearby metal from the lightning protection system, or if it is not possible, to connect the metalwork to the lightning protection system with an appropriate bond.

4.8.4 Design of Lightning Protection for a Centralised PV Mini-Grid System in the Sample Village Using a Computer Programme

It is necessary to design the lightning protection system for a centralised PV system in the sample village at Udon Thani. As a result, both a PV array field and a control building will be designed with lightning protection system.

4.8.4.1 For a PV Array Field

The PV array consists of 16 strings, with 15 series modules connected in a string. It is centre-tap grounded through a low resistance ground fault sensing shunt. This limits the current-to-ground electrical potential to one-half of the voltage across the source circuit terminals [48]. A single point ground is established on the common neutral conductor, so that there is only one system ground, not two. Mid-point grounding of the array through a resistor has the following advantages:

- Single line-to-ground fault current can be limited to a chosen level thus reducing possible burning and melting in faulted circuits and mechanical stress in circuits carrying fault current.
- Detection of ground fault current is facilitated by de-coupling neutral and ground.

However, the primary disadvantage is requiring ground fault detection and neutral-to-ground lightning arrester equipment. All structural frames, such as the module frame and supporting structure frame, must be grounded as shown in Figure 4.37.

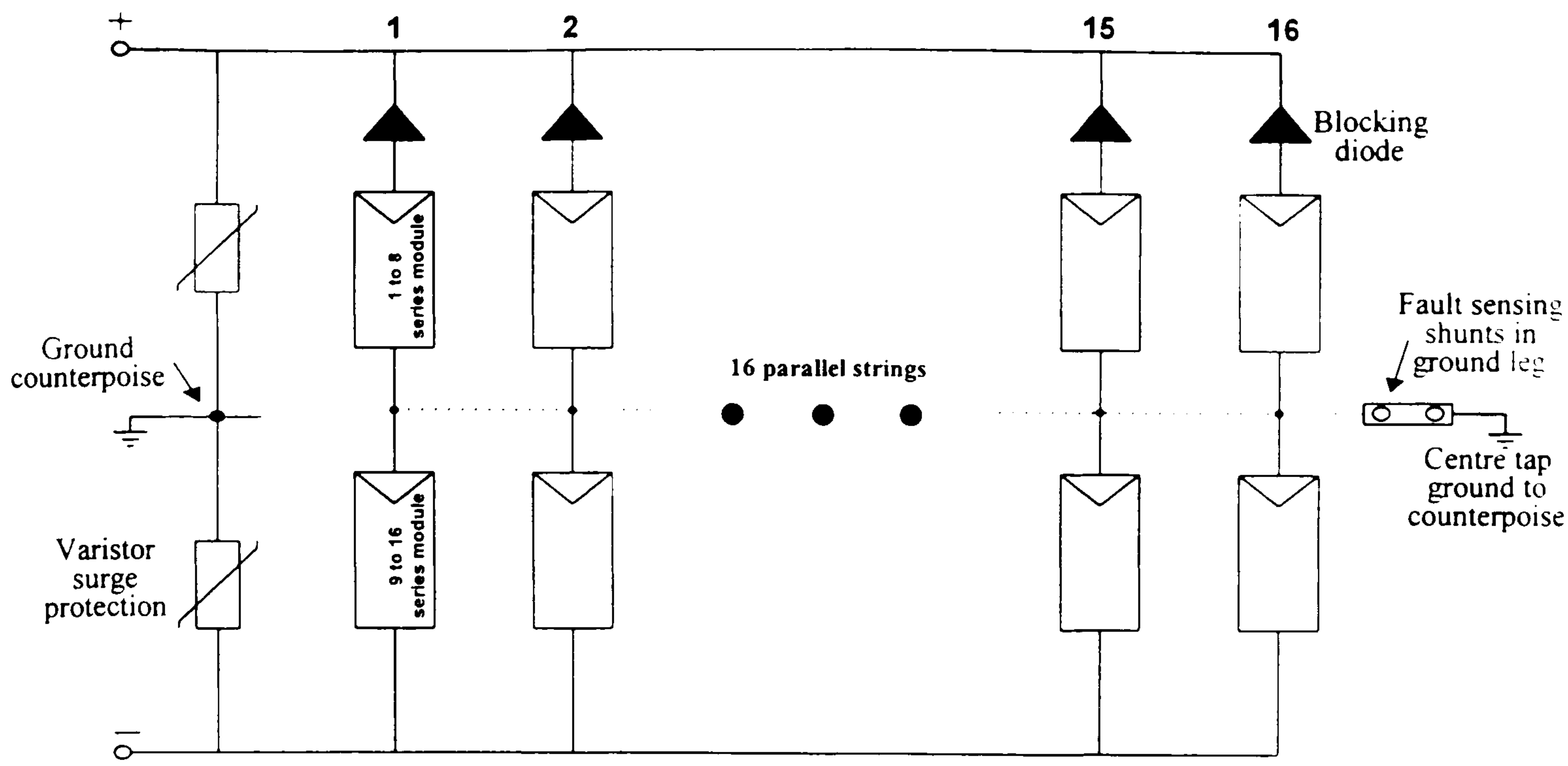


Figure 4.37 Conceptual design for lighting protection of an array circuit

4.8.4.2 For Electrical Equipment in Control Building

This depends on the dimension of the building and the shape of roof (see Table 4.18 and Figure 4.38).

4.8.5 Input Data and the Results

Tables 4.11 to 4.18 and some equations above are concerned in the process of calculation. They are also contained as an input of a computer's source programme. The details of the flow diagram of a computer programme can be seen in appendix B. The input and results of this programme can be printed out as follows:

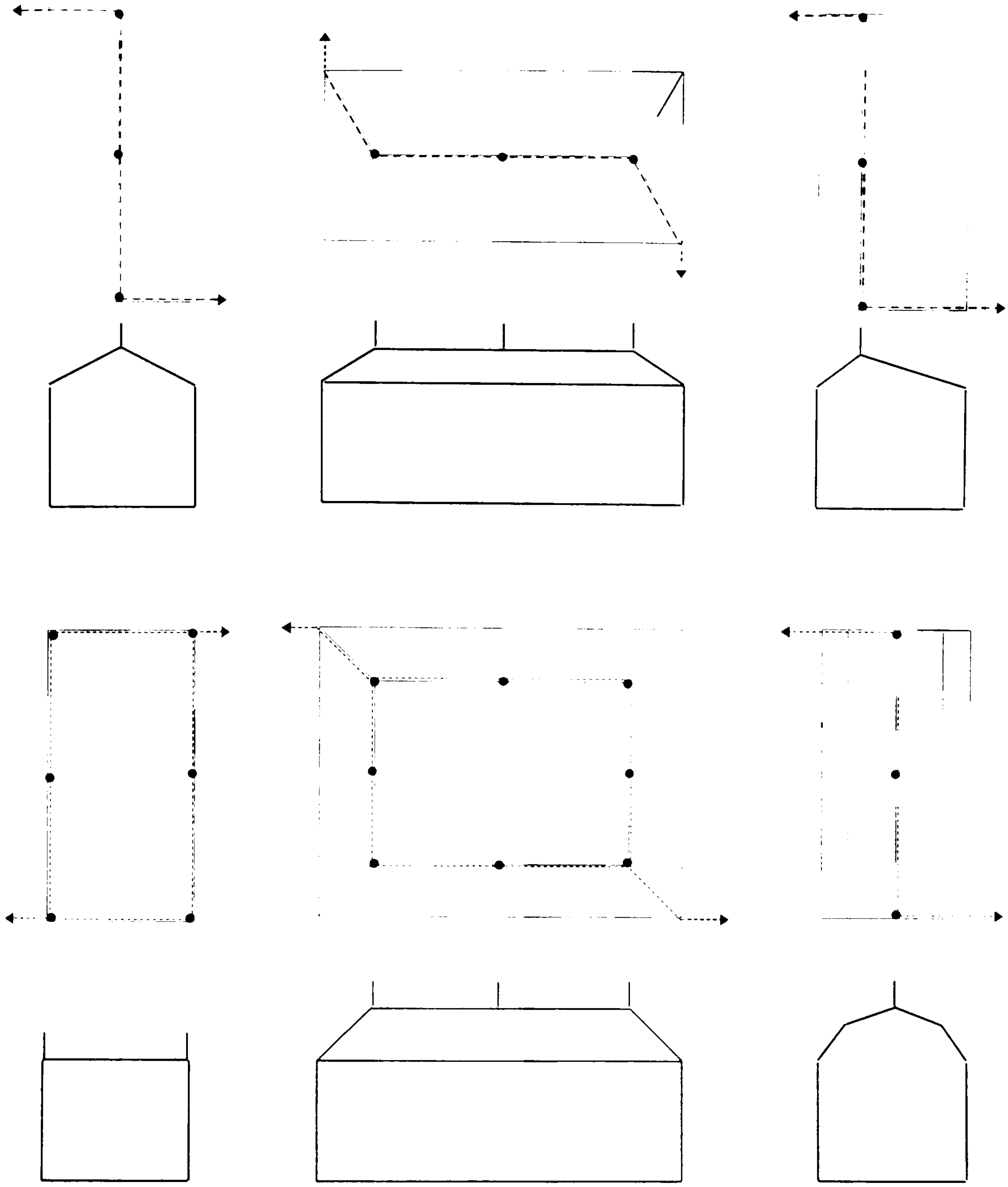


Figure 4.38 Installation of air terminators in different roof types of building.

:: This design is based on The British Standard BS 6651 ::

: Lightning protection system for PV array field :
dimension of PV array field :

total width = 20.0 metres
total length = 28.0 metres
total height = 1.5 metres

: Weighting Factor :

weighting factor a = 1.0
weighting factor b = 0.8
weighting factor c = 1.0
weighting factor d = 2.0
weighting factor e = 0.3
weighting factor f = 1.0
weighting factor g = 2.0
weighting factor h = 0.3
no. of lightning flashes/km2/year = 4.7
effective area = 710.6 metres
overall risk factor (ORF) = 0.001603
A significant result : *Lightning protection is desirable.*

: Lightning protection system for control building :

total width of control building = 10.0 metres
total length of control building = 12.0 metres
area of surrounding ground = 35815.9 m^2
incoming mains = 6000.0 m^2
data line = 6000.0 m^2
total collection area = 47935.9 m^2
the probability of strikes on the area 1 flash in 4.4 years
the risk of occurrence = 0.135179
surge protection is required suitable for '*medium*' level exposure environment
no. of down conductors = 2
no. of air terminals = 3
no. of earth electrodes = 2
minimum size of down conductor = 50 mm^2 (bare copper conductor)
the length of rod electrode = 8 feet and diameter = 0.75 inches

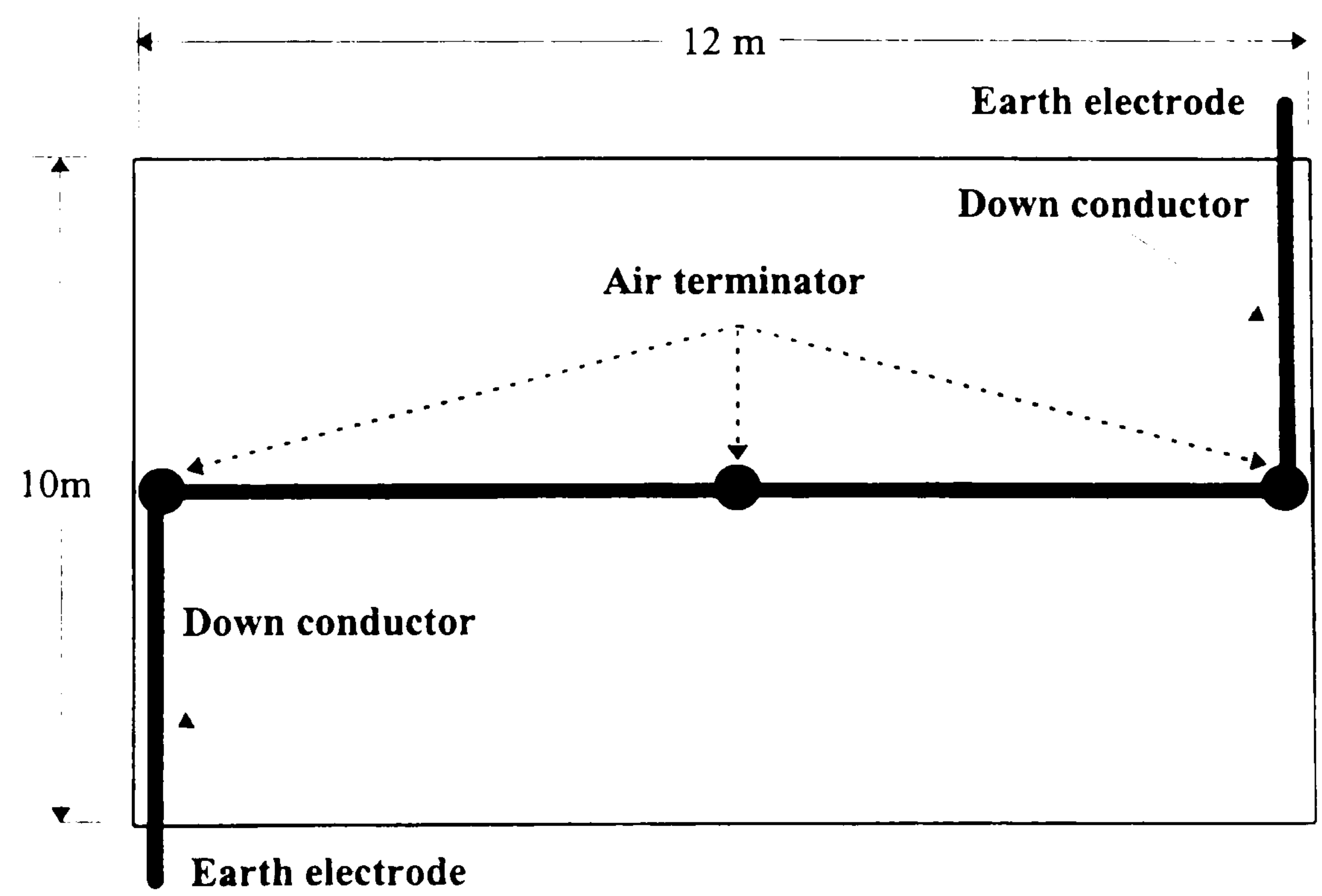


Figure 4.39 Air terminators and down conductors arrangement on slope roof of the sample control building

4.9 Protective Equipment and Electric Cable Sizing for a Centralised PV Mini-Grid System in the Sample Village Using a Computer Programme

As can be seen from Figure 4.40, there are a number of protective device used for protection of the system's components to avoid any damage from short circuit and over current failure. This protective device needs to be suitably sized based on the current flow through the circuits. In addition, the size of the electrical cable of each main feeder and branch circuit needs also to be sized. The design can be done by a computer programme that to be specifically developed for this work. The details of the flow diagram of this program can be seen in appendix B.

4.9.1 Input Data and the Results

The input and results of this computer programme can be found as follows:

: DC Wiring Specification for Array Circuit :

nominal system voltage = 240.0 VDC
maximum current flows through cable between modules = 5.0 A
rating of over-current protection (fuse or CB) = 10 A
maximum allowable percent of voltage drop = 2.0 %
type of conductor = THW
wire size = 2.5 mm^2

: DC Wiring Specification for Battery Circuit :

nominal system voltage = 240.0 VDC
maximum current between battery and battery = 100.0 A
rating of over-current protection (fuse or CB) = 125 A
maximum allowable percentage of voltage drop = 2.0 %
type of conductor = THHN
wire size = 35.0 mm^2

There is no branch circuit for DC load

: AC Wiring Specification :
The number of branch circuits = 4

branch circuit no. 1
nominal system voltage = 220.0 VAC
maximum current that can flow through cable = 0.23 A
rating of over-current protection (fuse or CB) = 6 A
maximum allowable percentage of voltage drop = 2.0 %
type of conductor = THW
wire size = 2.5 mm^2

branch circuit no. 2
nominal system voltage = 220.0 VAC
maximum current that can flow through cable = 2.90 A
rating of over-current protection (fuse or CB) = 6 A
maximum allowable percentage of voltage drop = 2.0 %
type of conductor = THW
wire size = 2.5 mm^2

branch circuit no. 3
nominal system voltage = 220.0 VAC
maximum current that can flow through cable = 5.0 A
rating of over-current protection (fuse or CB) = 10 A
maximum allowable percentage of voltage drop = 2.0 %
type of conductor = THW
wire size = 2.5 mm^2

branch circuit no. 4
nominal system voltage = 220.0 VAC
maximum current that can flow through cable = 0.19 A
rating of over-current protection (fuse or CB) = 6 A
maximum allowable percentage of voltage drop = 2.0 %
type of conductor = THW
wire size = 2.5 mm^2

: Wiring Sizing Specification of Grounding System :

maximum current of main protective equipment = 100.0 A
wire size = 10.0 mm^2 (bare copper conductor)

Note: THW and THHN are the type of electrical insulation,

THW: Moisture and Heat-Resistant Thermoplastic,

THHN: Heat-Resistant Thermoplastic with Nylon (for battery cable)

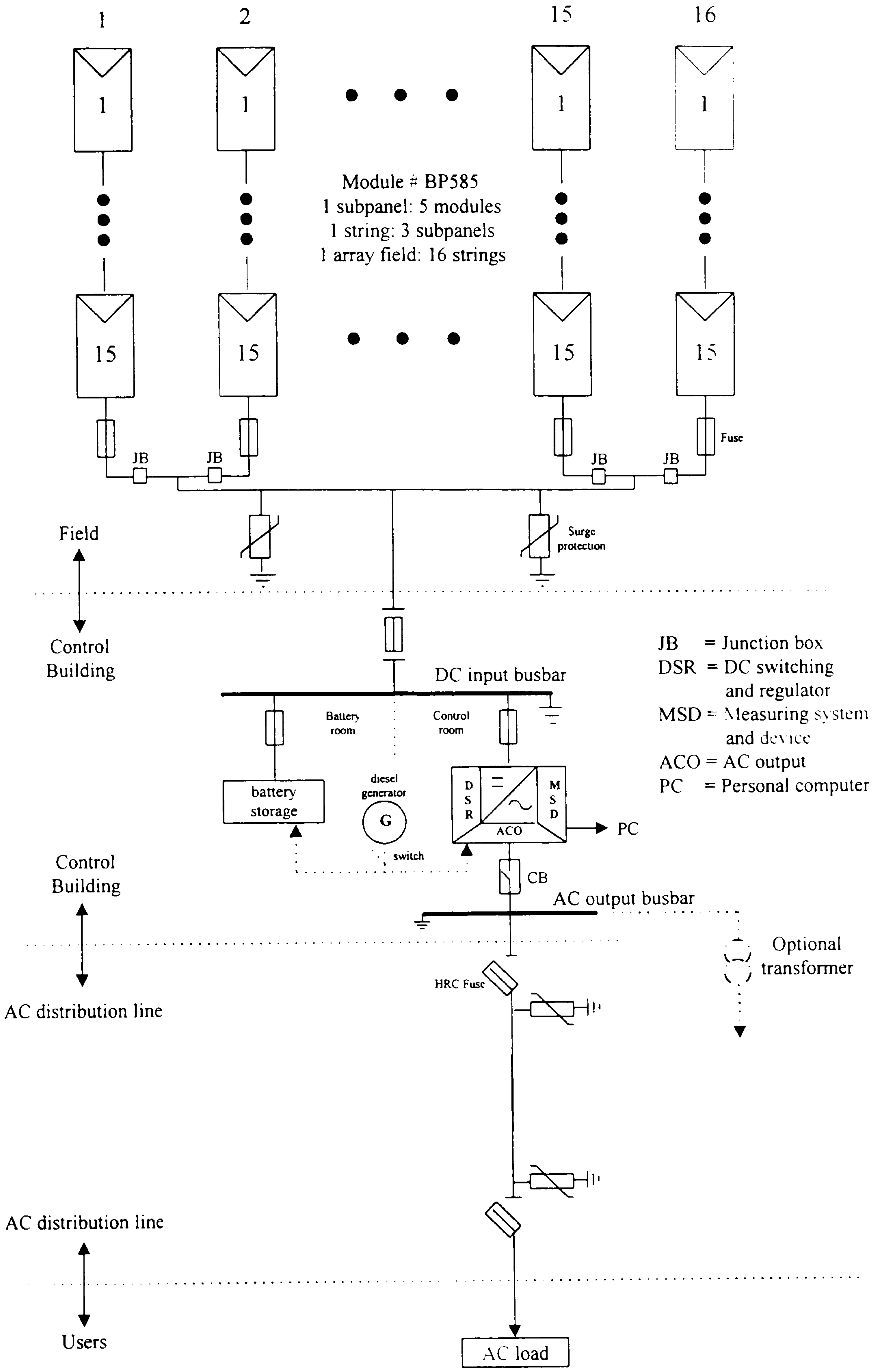


Figure 4.40 Electric diagram of a centralised PV system in the sample village

DC Wire Sizing Specification

WORK SHEET # 1 (a Centralised Mini-Grid System)					
Description	System voltage (V)	Maximum current (A)	Allowable voltage drop (%)	Wire size (mm^2)	Wire type
Array Circuit					
Module to Module	240	5[1]	2	2.5	THW
Array to Control Building	240	75.52[2]	2[3]	35	THW
DC Circuits					
Battery to Battery	240	100	2	35	THHN
Charger to Battery	240	75.52	2	35	THW
Battery to Inverter or Converter	240	100	2	35	THHN
Battery to DC load	N/A				
Branch Circuit					
1. N/A					
2. N/A					
3. N/A					
4. N/A					
System Grounding	Wire Size (mm^2)		Wire Type		Type of Earth Ground
Equipment Ground	-		-		-
system	10		Bare copper		To Ground Rod

Design Notes:

1. Maximum short circuit current
2. PV array can generate
3. Maximum length 30 metres

AC Wire Sizing Specification

WORK SHEET # 2 (a Centralised Mini-Grid System)					
Description	System voltage (V)	Maximum current (A)	Allowable voltage drop (%)	Wire size (mm^2)	Wire type
AC Circuit					
Inverter to AC load	N/A				
AC Power Distribution line	220	32.30	2[1]	120	THW[2]
Branch Circuit					
1.Main Feeder for Each Household	220	0.23[3]	2	2.5	THW
2.Pumping Load	220	2.9[4]	2	2.5[5]	THW
3.Feeder for Community Centre	220	5	2	2.5	THW
4. Street lighting	220	0.19	2	2.5	THW
System Grounding	Wire Size (mm^2)		Wire Type		Type of Earth Ground
Equipment Ground	6		Bare copper		To ground rod
system	-		-		-

Design Notes:

1. Maximum length of AC power distribution line is 500 metres
2. Single core
3. Power factor is corrected (PF = 0.85)
4. Data from GRUNDFOS's manufacturer # SQ3-30
5. Pump/motor 600 w single phase 50 H_z

Protection Components

WORKSHEET # 3 (a Centralised Mini-Grid System)							
Circuit	Protection Device (No.)				Rated Current (A)	Rated voltage (V)	Description
	CB	Fuse	Switch	Surge			
Array output		16			10	250	DC fuse
Array output				2	5000	250	Varistor
DC input			1		100	250	Disconnected Sw.
Battery		1			100	250	HBC
Controller to inverter		1			100	250	"
AC output	1				100/225[3]	380	AC circuit breaker
AC distribution line system		2			80	250	HBC
Each household		100			2	250	AC fuse[4]
Pumping		1			10	250	AC fuse[5]
Community centre	1				10	250	AC circuit breaker[6]
Street lighting		1			2	250	AC fuse
System Grounding	Wire Size		Wire Type		Type of Earth Ground		
Equipment Ground	6		Bare Copper		To ground rod		
System	10		Bare Copper		To ground rod		

Design notes:

1. HRC fuse links with bolted connections, breaking capacity 40 kA at 250 VDC
2. HBC ceramic industrial fuses with leaf spring fuse blown, breaking capacity ≥120 kA
3. CB rated 100 ampere-trip / 225 ampere-frame
4. Cartridge fuse , breaking capacity 50 kA at 380 V
5. Time delay fuse type, breaking capacity 50 kA at 380 V
6. Circuit breaker single phase 2 poles, breaking capacity 16 kA

Lightning Protection System Specification

WORK SHEET # 4 (a Centralised Mini-Grid System)						
Items	Cable (Area) (mm^2)	Cable Type or (quantity)	Conductor or Connector Type			Dimension (mm)
			Copper	Aluminium	galvanized	
Air Terminator	50	(3)	✱			8 (dia)
Down Conductor	50[1]	THW (2)	✱			8 (dia)
Earth Electrode	50	(2)	✱			See Note 2
Others						
a. Bonds ■ external rod ■ internal rod	 50 33		 ✱ ✱			 8 (dia) 6.5 (dia)
b.						
c.						

Design Notes:

1. Bare conductor
2. Length 8 feet and ∅ ¾ inch
3. Dimension of control building (w×l×h) = 10×12×3 m

4.10 The Economic Analysis of Stand-Alone PV Power Systems

The PV systems are most competitive where small amounts of energy are required far from the utility grid. The economic viability of a PV system must be assessed relative to the alternatives, for example diesel, extending the grid and so on. A complete approach to economic appraisal is to use life cycle costing because it is a term commonly used to describe a general method of economic evaluation by which all relevant costs over the life of a project are accounted for when determining the economic efficiency of a project [49,50].

4.10.1 Life Cycle Costing (LCC) Analysis

The LCC analysis is the appropriate method for comparing different electrification options. The initial costs and all future costs for the entire operational life of a system are considered. To make a meaningful comparison, all future costs and benefits have to be discounted to their equivalent value in today's economy. All the future costs and benefits are discounted to the present worth or " present day values". To achieve this, each future cost is multiplied by a discount factor calculated from the discount rate. The discount rate expresses how the value of money decreases the further into the future it is received. For example a discount rate of 8% per year would mean that, in real terms, it is equivalent for a customer to receive $100 now or $108 in one year's time. Therefore a cost of $108 one year from now has a present worth of $100. High discount rates mean that a low value is placed on future costs and benefits. The discount rate can be viewed either as interest that would have to be paid on a loan or the interest that has been lost by spending capital rather than leaving it invested in the bank. It is worth mentioning that such economic analysis does not take into consideration such factors as environmental benefits [51], where PV does not add to environmental pollution like conventional energy sources. The benefit of PV having a higher reliability factor, hence giving a superior service, is sometimes omitted. However, all calculations are done relative to general information, so that all costs are expressed in today's money. There are a number of factors that must be taken into account as the input for calculation of LCC to get the economic indicators. The input consists of these factors as follows:

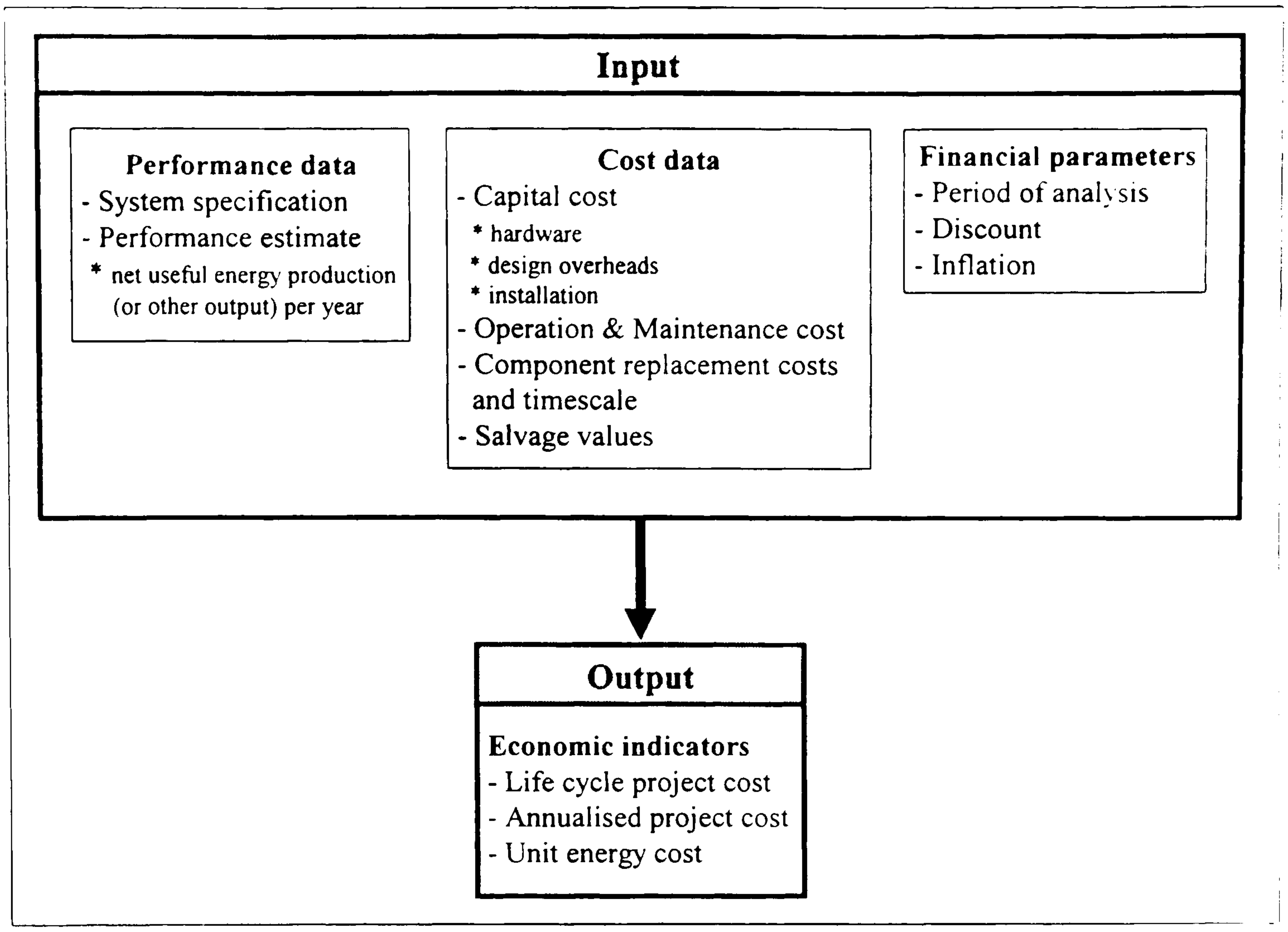


Figure 4.41 Outline methodology of LCC

The calculation of LCC requires values to be known as follows:

- *Period of analysis (n)*

  The lifetime of the longest lived system under comparison.

- *Excess inflation (i)*

  The rate of price increase of a component above or below general inflation (this is usually assumed to be zero).

- *Discount rate (d)*

  The rate (relative to general inflation) at which money would increase in value if invested (typically 5-10%).

- *Capital cost*

  The total initial cost of buying and installing the system.

- *Operation and Maintenance (O&M)*

  The amount spent each year in keeping the system operational.

- *Replacement cost*

  The cost of replacing each component at the end of its lifetime (if less than the life time of the whole system).

4.10.2 Calculation of the Present Worth (PW)

There are two types of calculation that are used in the LCC when expressing a future cost or benefit as its present worth. Firstly, it is used to calculate the PW of a single payment, say the replacement of a battery after 5 years. Secondly, it is used to calculate the total net present worth of a recurring cost, such as maintenance costs or annual fuel. This is the sum of many discounted single payments over the analysis period of n years. The PW is given by [49-54] :

- ***Single payment***

$$PW = C_r . P_r \tag{4.16}$$

where

$$P_r = \left(\frac{1 + i}{1 + d} \right)^n \tag{4.17}$$

C_r = a future cost or benefit

i = inflation rate

d = discount rate

n = a period of analysis in years

- ***Annual payment***

For a payment or benefit (C_a) occurring annually for a period of n years that is inflated at a rate " i " and discounted at a rate " d ", the present worth is given by :

$$PW = C_a . P_a \tag{4.18}$$

where

$$P_a = \left[\frac{a\left(1 - a^n\right)}{(1 - a)} \right] \tag{4.19}$$

and

$$a = \left[\frac{(1 + i)}{(1 + d)} \right] \tag{4.20}$$

or

$$P_a = \frac{\left[\frac{(1+i)}{(1+d)}\right]\left[\left|\frac{(1+i)}{(1+d)}\right|^n - 1\right]}{\left[\frac{(1+i)}{(1+d)} - 1\right]} \qquad (4.21)$$

To avoid the complex equations above, Tables in appendix D can be used. They give the factors P_r and P_a respectively for selected values of n, i and d.

The interest rates and discount rates used should be relative to general inflation. Hence costs are only assumed to inflate or deflate if their prices are changing relative to all the other prices. Nevertheless, as long as both discount and inflation rates are expressed in the same way (i.e. both excluding general inflation or both including general inflation) the resulting PW will be the same. Normally, inflation rates in Tables D1 and D2 in appendix D are assumed to be zero. In this case, Table D3 can be used. The value found using d and n is then multiplied by the expense C_r to obtain the PW (the table assumes that i = 0). Similarly, Table D4 in appendix D may be used, the value found using d and n is then multiplied by the expense C_a to obtain the PW (the table assumes that i = 0).

4.10.3 Calculation of the Life Cycle Cost

For each payment to be made during the life time of the system, the present worth can therefore be determined using the discount factors P_r and P_a. The sum of all PW is the total life cycle cost of the system [55-57].

$$LCC = C_{cap} + C_{o\&m} + C_{rep} + C_{sal} \qquad (4.22)$$

where

LCC = life cycle cost.

C_{cap} = capital cost (the value of the total initial investment).

$C_{o\&m}$ = operation and maintenance cost (excluding fuel cost and major replacement cost, incurred over n years.

C_{rep} = discounted value of replacement costs of major items (e.g. batteries, power conditioner)

C_{sal} = salvage or scrap value at the end of system life.

There are two ways that the LCC is commonly used to provide more intelligible expressions of system cost.

4.10.3.1 Annualised Life Cycle Cost (ALCC)

The ALCC is the life cycle cost expressed with a constant cost per year. It is the annual expenditure required to pay for the system over its lifetime and includes the cost of replacements on borrowed capital. The LCC must be divided by the factor P_a, found using the chosen discount rate, inflation rate, and the number of years equal to the analysis period. This is really the reverse process of discounting and the result is expressed in \$/year for each system.

$$ALCC = \frac{LCC}{P_{a(n)}} \tag{4.23}$$

4.10.3.2 Cost of Electricity (COE)

The COE is probably the most useful figure for comparing two energy technologies or between different remote area power supply systems in any situation. It expresses the average cost of generating each useful unit of energy during the system lifetime. If the system is generating electricity then it can be calculated from ALCC as follows:

$$COE = \frac{\text{ALCC } (\$/\text{year})}{\text{electric energy produced } (\text{kWh})} \tag{4.24}$$

4.10.4 Economic Analysis of a Centralised PV Mini-Grid System in the Sample Village

According to the previous design of a centralised PV mini-grid system in the sample village at Udon Thani province of Thailand, the cost of the system has been analysed by the LCC method. The key assumptions used in estimating the cost are listed in Table 4.19. The details of the analysis are also shown in Table 4.20.

Table 4.19 Key assumptions used in estimating cost in US\$ (lifetime)

Life cycle period 20 years	Regulator \$7 / amp (5)
Discount rate 10 %	Charger \$6 / amp (10)
Inflation 5 %	Inverter cost \$650 / kW (10)
Module cost \$6 / kW_P (20)	Fluorescent lamp \$3-5 / lamp (2)
Battery cost \$150 / kWh (5)	LPG sodium \$25 / lamp (2)

Table 4.20 Life cycle cost analysis of a centralised PV mini-grid system

Project/Site : Udon Thani, Thailand		**Type of system :** PV centralised system (mini grid)		
1. Financial parameters	*Symbol*	*Values*	*Unit*	*Remark*
Period of analysis	n	20	years	project lifetime
Discount rate	d	0.10		10%
Inflation rate	i	0.05		5%
Discount factor	a	0.954		a = (1+i)/(1+d)
Annualised factor	$P_{a(n)}$	12.65		$P_{a(n)} = a(1-a^n)/(1-a)$
2. System specification and performance				
Energy Load Demand				
Daily load	L_d	33.72	kWh/day	100 households
Annual load	L_a	12307.8	kWh/year	$365 * L_d$
Solar Module				
Array size	S_a	20400	W_P	
Module unit price	S_p	6	$/$W_P$	silicon cells
Lifetime	S_{lt}	20	years	
Battery				
Battery capacity	B_c	384	kWh	
Battery unit price	B_p	150	$/kWh	
Lifetime	B_{lt}	5	years	
Controller				
Charge controller	R_c	100	amp	
Charge controller unit price	R_p	7	$/amp	
Lifetime		5	years	
Power Conditioner				
Inverter size	I_s	16	kW	
Inverter unit price	I_p	650	$/kW	
Lifetime		10	years	
Battery charger	D_{BV}	100	amp	
Battery charger price	D_p	6	$/amp	
Lifetime		10	years	
Measuring / Controlling Equipment				
Measuring systems		9000	$	
Lifetime		10	years	
Back - Up Machine				
Diesel generator	G_s	18	kVA	pf = 0.85
Generator price	G_p	7600	$	$4000+(200*G_s)$
Lifetime		10	years	
Fuel				
Energy content	G_{f1}	5	kWh/litre	
Energy consumption	G_{f2}	7.84	litres/day	$G_{f2} = L_a / G_{f1}$
Fuel unit price	G_{fp}	0.9	$/litre	2000 in Thailand
End-user loads				
Fluorescent lamp 8 W		300	$	100 lamps
Fluorescent lamp 18 W		400	$	100 lamps
Fluorescent lamp 36 W		50	$	10 lamps
Low pressure sodium lamp 26 W		500	$	20 lamps
Lifetime		2	years	
Inverter & lamp housing (street light)		400	$	20 sets
Radio		3000	$	100 sets
TV & VCR		400	$	
Motor & Pumping		4000	$	
Refrigerator/Freezer		1400	$	
Lifetime		10	years	
Mounting and Foundation				
Mounting & Foundation unit price	K_p	0.5	$/$W_P$	
Lifetime	K_{lt}	20	years	

3. Cost data				
PV array	C_{pv}	122400	$	$C_{pv} = S_a * S_p$
Battery	C_{bat}	57600	$	$C_{bat} = B_c * B_p$
Charge controllers	C_{reg}	700	$	$C_{reg} = R_c * R_p$
Battery charger	C_{bc}	600	$	$C_{bc} = D_{bc} * D_p$
Inverter	C_{inv}	10400	$	$C_{inv} = I_s * I_p$
Diesel generator	C_{gen}	7600	$	
Generator installation (10%)	C_{gin}	760	$	lifetime 10 years
Generator O&M (12%/year)	C_{gop}	912	$/year	$C_{gop} = 0.12*C_{gen}$
Fuel		141	$/year	20 days (120h)/year
Mini grid & switching gear (500m)	C_{grid}	9000	$	lifetime 20 years
Fluorescent lamp 8 W		300	$	
Fluorescent lamp 18 W		400	$	
Fluorescent lamp 36 W		50	$	
Low pressure sodium lamp 26 W		500	$	
Inverter & lamp housing (street light)		400	$	lifetime 10 years
Radio		3000	$	
TV & VCR		400	$	
Motor & Pumping		4000	$	
Refrigerator/Freezer		1400	$	
Measuring systems		7000	$	
Lighting protection system	C_{lps}	1224	$	$C_{lps} = 0.01*C_{pv}$
Mounting & Foundation	C_{sw}	10200	$	$C_{sw} = S_a * K_p$
Installation (20%)	C_{in}	24480	$	$C_{in} = 0.2*C_{pv}$
a) Capital Cost	C_{cap}	**263467**	$	
Operation & Maintenance (2%)	C_{om}	2448	$	$C_{om} = 0.02*C_{pv}$
b) Life Cycle O&M Cost	$C_{o\&m}$	**30967.2**	$	$C_{om} * P_{a(n)}$
Replacement Cost	*Yr.(i)*	*PW*		
(i) Battery		110592		every 5 years
(ii) Charge controller		1344		every 5 years
(iii) Inverter		5040		every 10 years
(iv) Generator & installation		4435.2		every 10 years
(v) Fuel		1734.3		
(vi) O&M for generator		9446.4		
(vii) Battery controller		378		every 10 years
(viii) Measuring systems		4410		every 10 years
(ix) End-user loads				
-Fluorescent lamp 8 W		1860		every 2 years
-Fluorescent lamp 18 W		2486		every 2 years
-Fluorescent lamp 36 W		310		every 2 years
-Low pressure sodium lamp 26 W		3100		every 2 years
-Inverter & lamp housing		252		every 10 years
-Radio		1890		every 10 years
-TV & VCR		252		every 10 years
-Motor & Pumping		7680		every 5 years
-Refrigerator/Freezer		882		every 10 years
c) Life Cycle Replacement Cost	C_{rep}	**156091.9**		
d) Salvage	C_{sal}	**-0.0**		
4. Economic indicator				
Total Life Cycle Cost	LCC	**450526.1 US$**		LCC = a+b+c+d
Annualised LCC	ALCC	**35614.7 US$/year**		$ALCC = LCC/P_{a(n)}$
Cost of Electricity	COE	**2.89 US$/kWh**		$COE = ALCC/L_a$

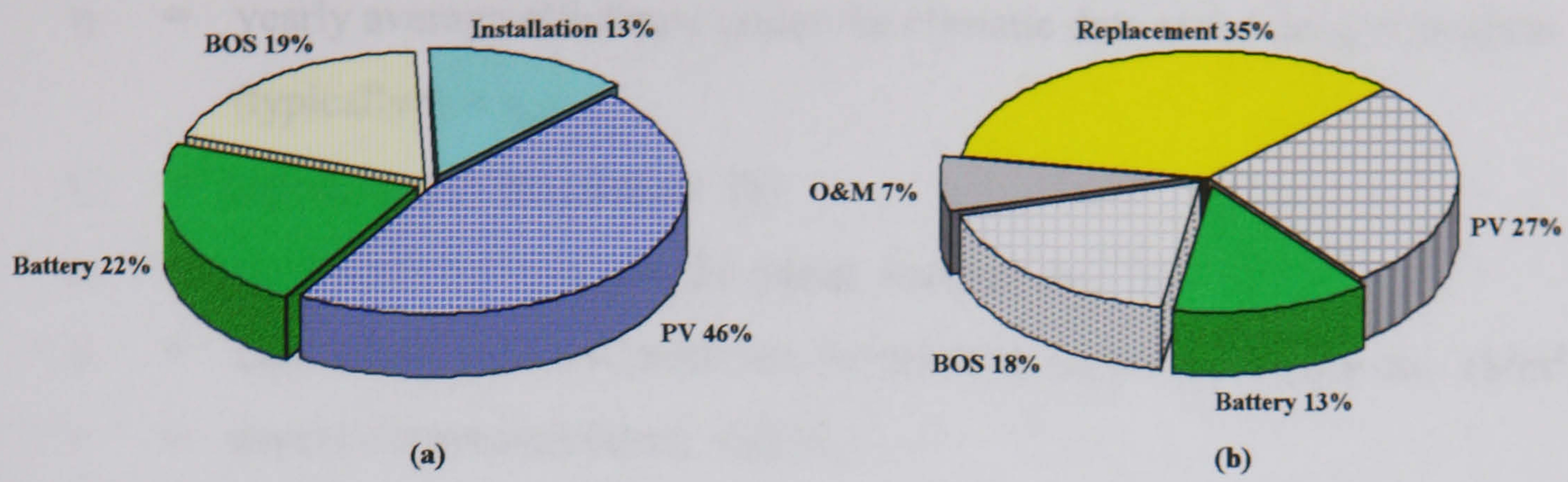


Figure 4.42 a) capital cost of a centralised PV mini-grid system
b) life cycle cost of a centralised PV mini-grid system

4.10.5 Economic Competitiveness of a PV System

In general, energy technology can be mainly divided into two stages, namely primary and secondary energy. The secondary energy is obtained after primary energy's conversion into the desired type of energy, for example converting gas into electricity. In the case of solar radiation the cost of the primary energy is free. In this topic the costs for the secondary energy will be discussed. A simple model will be developed which allows an estimate of the costs of PV generated electricity with a surprisingly high degree of reliability and without going into the details of the cell. The cost of electricity is flexible to allow study of various influences on the prices. In order to calculate the cost the parameters below are concerned with the economic equations. The cost is expressed in US$. They are as follows [59]:

C = cost of electricity ($/kWh)

E_{pv} = energy generated by the PV station (kWh/year)

P_y = yearly payments ($/year)

M = annual maintenance cost ($/year)

P_o = output power of PV system at STC (kW_p)

A_m = solar irradiance (kW/m^2)

η_p = panel efficiency at standard test conditions

A_p = panel area (m^2)

N_p = number of panels

D_y = solar irradiation throughout the year at the design location ($kWh/m^2/year$)

η = yearly average efficiency under the climatic data at the design location (typically $\eta < \eta_p$)

C_i = capital cost of investment (\$)

α = coefficient or rated cost for panel, inverter etc. (\$/kW)

β = coefficient or area related cost for the land, support structure etc. (\$/m^2)

γ = power output coefficient (\$/kW$_p$)

A_s = area of the power station (m^2)

The equation of energy price can be written as follows:

$$C.E_{pv} = P_y + M \tag{4.25}$$

The nominal power output of the power station is defined as usual under the standardised solar irradiance (A_m) of 1 kW/m^2, hence:

$$P_o = \eta_p A_m A_p N_p \tag{4.26}$$

The energy generated per year is given by

$$E_{pv} = \eta D_y A_p N_p \tag{4.27}$$

giving,

$$\eta = \frac{E_{pv}}{D_y A_p A_m} \tag{4.28}$$

and

$$P_o = \frac{\eta_p}{\eta} \cdot \frac{A_m}{D_y} \cdot E_{pv} \tag{4.29}$$

Generally, η is smaller than η_p and η may also become smaller if non-ideal positioning of the panels has to be accepted (i.e., if the panels are used as a claddings, used on roofs which are badly oriented to the incident radiation etc.). In addition, there are a number of financing options which may be considered : (i) Equal periodic repayments of a loan, thus each payment includes amortisation of the capital and the interest of the remaining capital at each period. (ii) Period amortisation with a given fraction of the interested capital (or depreciation) plus the interest of the remaining capital. Mode (ii) is slightly more favorable if the total amount of interest which has to be paid over the whole life of the system is considered. It is assumed that if mode (i) of financing is chosen, then the yearly payment (P_y) has to be calculated from the interest rate (r) and the number of years of the loan. Thus

$$\frac{P_y}{C_i} = f = \frac{r}{\left[1 - \frac{1}{(1+r)^n}\right]} \tag{4.30}$$

C_i is the sum of costs for the panels, inverter, the projection of the power station etc., and of those which are related to the area, for example mechanical support structures, electrical installations and land cost. Thus C_i is given by

$$C_i = \alpha P_o + \beta A_s \tag{4.31}$$

Using Equations 4.25 and 4.30, thus

$$C.E_{pv} = f(\alpha P_o + \beta A_s) + M$$

$$C = f\left[\alpha\left(\frac{\eta_p}{\eta}\cdot\frac{A_m}{D_y}\right) + \beta\left(\frac{A_s}{\eta D_y A_p N_p}\right)\right] + \frac{M}{\eta D_y A_p N_p} \tag{4.32}$$

However, it can be expected that the maintenance costs (M) are proportional to the size of the power station, so that it seems to be legitimate to put $M = \gamma P_o = \gamma(\eta_p A_m A_p N_p)$. Thus,

$$C = f\left[\alpha\left(\frac{\eta_p}{\eta}\cdot\frac{A_m}{D_y}\right) + \beta\left(\frac{A_s}{N_p A_p}\cdot\frac{1}{\eta D_y}\right) + \gamma\left(\frac{\eta_p}{\eta}\cdot\frac{A_m}{D_y}\right)\right] \tag{4.33}$$

The formula shown above can be used for determining the cost of electricity in which the coefficients α, β and γ are known. It is assumed that the maintenance costs are usually small compared with the yearly repayment whereby the value of γ becomes zero (γ=0). According to the design location at Udon Thani, the solar radiation (D_y) is about 1580 kWh/m^2-year. The ratio of A_m/D_y is 6×10^{-4} kW/kWh-year. Similarly, it is assumed that η_p/η and A_s/A_pN_p are both equal to 1.1, it implies that η_p and A_s are about 10% greater than η and A_pN_p respectively. Equation 4.33 can be rearranged according to the assumption above as follows: (if interest rate (r) = 10% and n = 20 years).

$$C = (8 \times 10^{-5})\left(\alpha + \frac{\beta}{\eta}\right) \tag{4.34}$$

It is now easy to calculate the cost of electricity as a function of α and β by using the efficiency η as a parameter. The equation 4.34 shows that for a cost of electricity of 0.2 \$/kWh, the power stations have to be lower than 2500 \$/kW. Therefore the area related costs would have to be zero. At present, the panel cost is between 3500 and

5000 \$/kW [60]. Similarly, the area related costs have to be smaller than 250 \$/m^2 at yearly average efficiency (η) of 10%. Since the power related costs would have to be zero for cost of electricity of 0.2 \$/kWh. The relationship of area related cost (\$/m^2), power related cost (\$/kW) and an average efficiency can be calculated with the value of C that is fixed at 0.2 \$/kWh. They are tabulated in Table 4.21 and are shown in Figure 4.43.

Table 4.21 Showing the relationship of α, β and η at C = 0.2 \$/kWh

C = 0.2						
η	α = 2500	α = 2250	α = 2000	α = 1750	α = 1500	α = 1250
	β	β	β	β	β	β
0.04	0	10	20	30	40	50
0.08	0	20	40	60	80	100
0.10	0	25	50	75	100	125
0.12	0	30	60	90	120	150
0.14	0	35	70	105	140	175
0.18	0	45	90	135	180	225
0.20	0	50	100	150	200	250

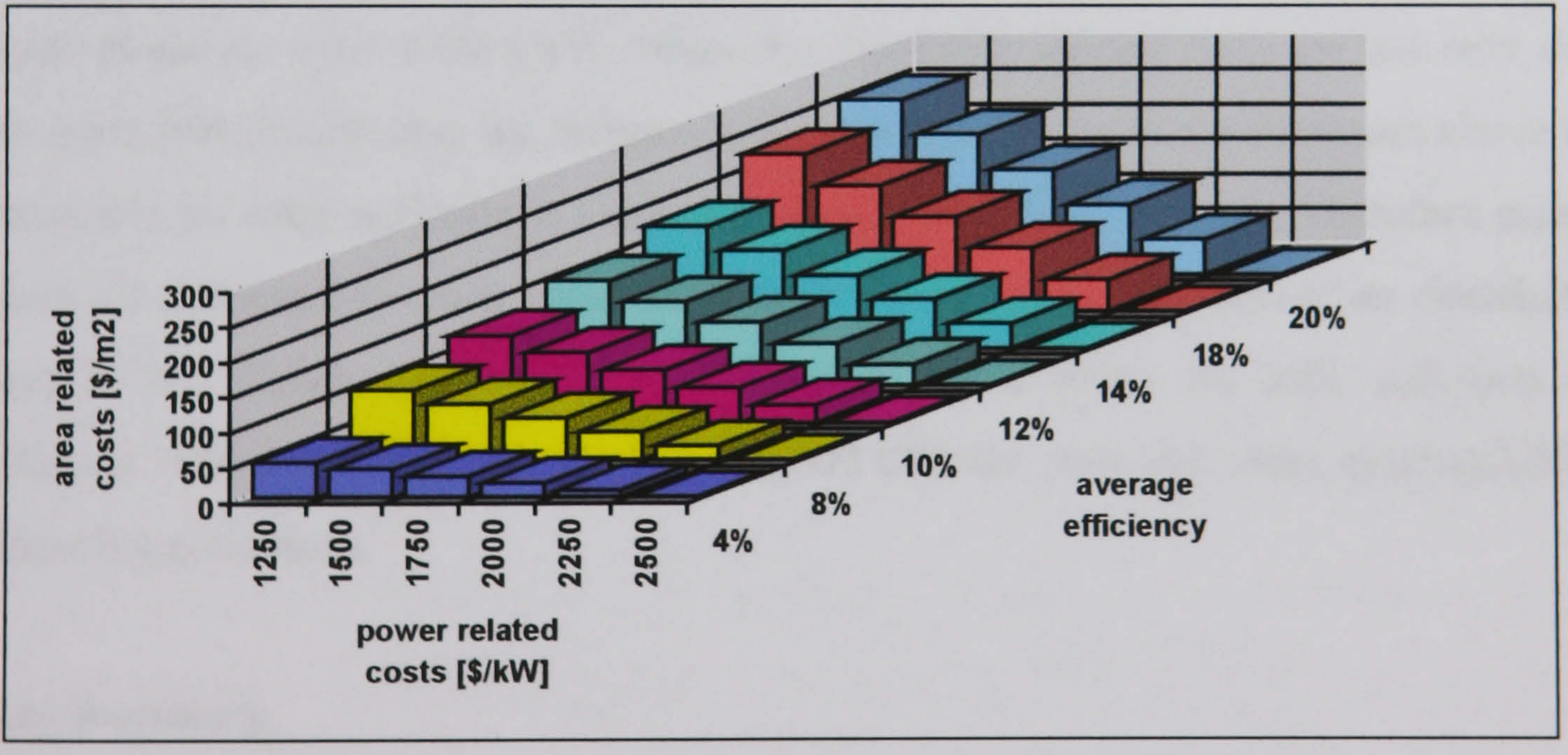


Figure 4.43 Area and power related costs with an electricity cost of 0.2 \$/kWh

As can be seen from Figure 4.43, the power related costs may vary between 2500 \$/kW and a final limit of 1250 \$/kW, and the area related costs between 250 \$/m^2, and a lower boundary of 50 \$/m^2. Both power and area related costs are very optimistic.

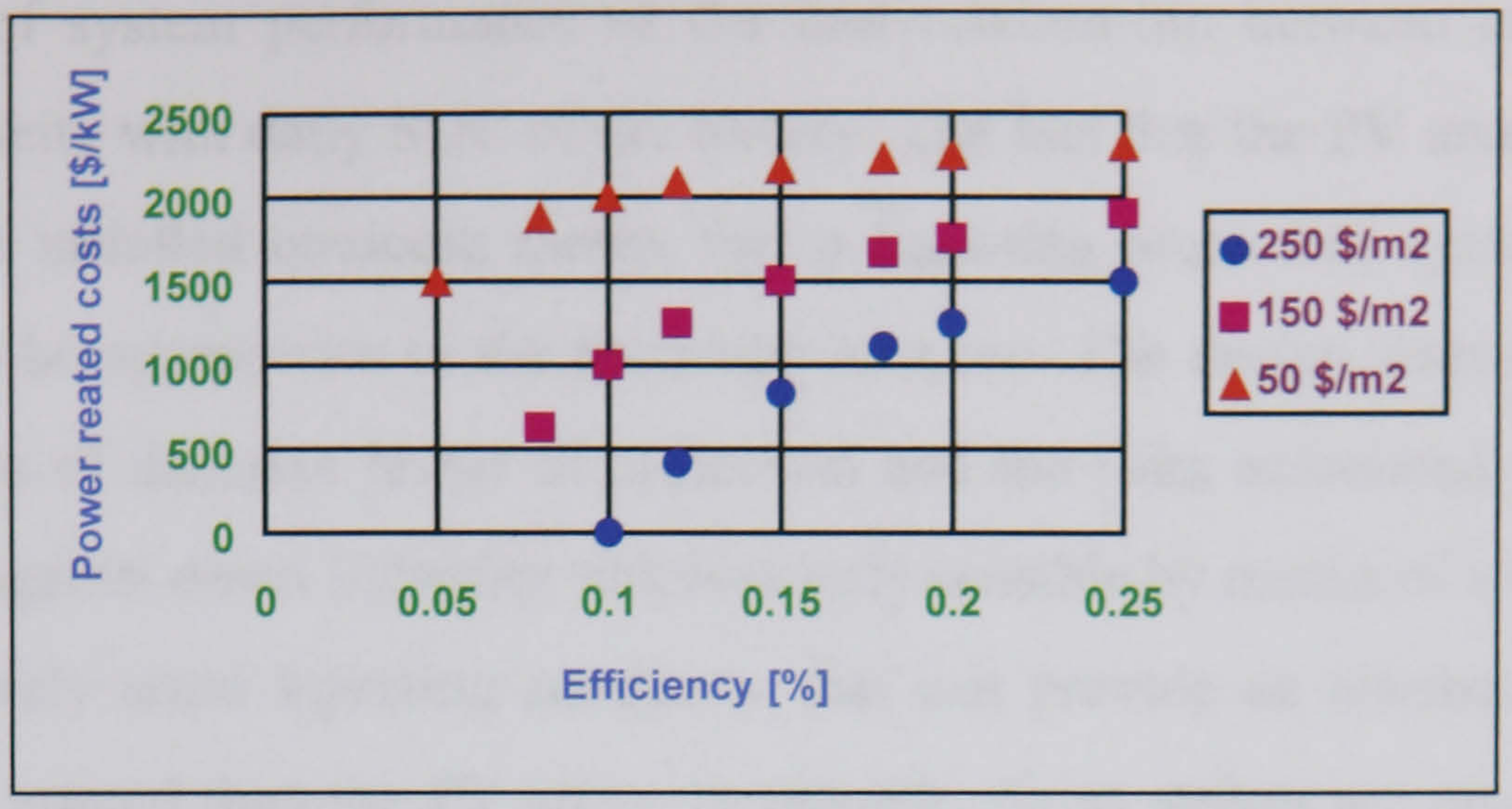


Figure 4.44 The power related costs as a function of efficiency assumed to be 0.2 $/kWh

The relationship between power related cost at an electricity cost (C) of 0.2 $/kWh, and efficiency is more clearly depicted in Figure 4.44. It shows that at an average efficiency of 10% (at C = 0.2 $/kWh) can be achieved at area and power related costs of 150 $/m^2 and of 1000 $/kW. For area related costs of 150 $/m^2 at an average efficiency of 15% (at C = 0.2 $/kWh) the power related costs might be as high as 1500 $/kW. It is indicated that only a power station with high efficiency that is over 10% may achieve the goal of allowing that cost of electricity at reasonable power related costs of greater than 1000 $/kW. However, the power related costs are not only the modules, but include also the inverter and so on. The methodical calculation above is presented for solar radiation at Udon Thani with 1580 kWh/m^2-year. Therefore panel costs are estimated to reach about 2000 $/kW in the future. The aim of an electricity cost of 0.2 $/kWh can only be reached at locations where the solar radiation is between 1100 kWh/m^2-year and close to 2000 kWh/m^2-year and under more suitable financing conditions.

4.11 Summary

To design a centralised PV mini-grid system in the rural village is complicated because there is much useful information needed. In fact, the first step of the design requires knowledge of the daily load demand in each household. The design approach is to calculate the array size and battery capacity. Daily average solar radiation at the design location is also strongly needed to be an input of the computer programme for prediction of system performance or the best relationship between array size and battery capacity with daily SOC of the battery. The fact that the PV array in this case needs to be installed outdoors means that a lightning protection system should be designed to be appropriate to the particular location. The design considers the cost-effectiveness of different levels of protection and the risks associated with a strike. Protection against direct lightning strikes is only possible by means of a well designed and adequately sized lightning conductor that can provide an alternative condition path to the ground than the PV array. In practice, direct strikes are rare and induced high voltage surges due to strikes nearby are more likely to damage wiring and system components. Lightning protection on the solar array can be protected with surge protection. For a control building should be protected against direct strokes with a complete lightning protection system. A mini-grid system in the village can be designed into 1 or 3 phase system depending on the output voltage type of inverter and load demand or load voltage. Usually, the PV array must be installed near to the loads, especially the farthest loads, to reduce the power loss in the electric cables and the size of conductor can be also reduced.

The economic analysis of a centralised PV mini-grid system in the sample village was evaluated by LCC analysis method. It can be applied to different PV systems. The results have shown that the annualised LCC and cost of electricity are 35614.7 US$/year and 2.89 US$/kWh respectively.

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Chapter 5

Design of Decentralised Stand-Alone PV Systems of Different Types

Chapter 5

5.1 Introduction

A centralised PV mini-grid system in the sample village has been designed previously (see chapter 4). The aim of this chapter is to design the decentralised or individual PV systems of different types based on the same load conditions and same village facilities with 100 households compared to a centralised PV mini-grid system. They are a battery charging station system, a pumping system, a PV system for the community facilities, a refrigeration system, a street lighting system and a solar home system. In fact, a battery charging station provides electrical power for charging the batteries used in each household. Other loads, such as public lighting, water pumping, refrigerator/freezer and community facility are designed as PV individual systems. The methodical analysis of this chapter consists mainly of how to design the system, presenting a system sizing method that can be completed by using design worksheets that are provided. An economic analysis of different PV system types is also presented by using the life cycle cost method. General considerations of each system component to be used in different system types are addressed based on the lessons learned from the previous PV systems installed.

5.2 PV Battery Charging Station

In many Thai rural villages, there is no access to electricity from the utility grid. Batteries have been used as a source of power to provide the small appliance loads, such as lamps, a radio and a black/white TV set. However, these batteries need to be charged after they are used until the capacities are critically reduced. Basically, local people who use the batteries have to transport their batteries to a city centre for charging and pick them up after the batteries are fully charged. This process may involve expenditure of time and money. As a result, PV systems are considered in terms of the battery charging stations (BCS) in rural villages, particularly in developing countries. They also provide battery-charging facilities for families that are using a car battery. The operating principles are exactly the same as those in other PV installations in which a battery is charged. Nevertheless, the load control system needs to be more sophisticated to ensure that the charging of each battery is properly controlled. In general, a main advantage of a BCS is to provide local charging points that can be separately established from the utility grid network. There are no inherent fuel costs or fuel supply problems, and unattended operation of equipment at remote sites is possible. They can also be suitably considered in rural areas which have medium to high of solar insolation, namely over 3 kWh/m^2/day. This is because a system cost will depend on the local solar insolation. A PV application for a BCS consists of a PV generator and charging controllers including monitoring devices, such as DC ammeters and voltmeters, fuses or circuit breakers. The batteries that need to be charged are transported by the villagers or users and picked up after the batteries are fully charged.

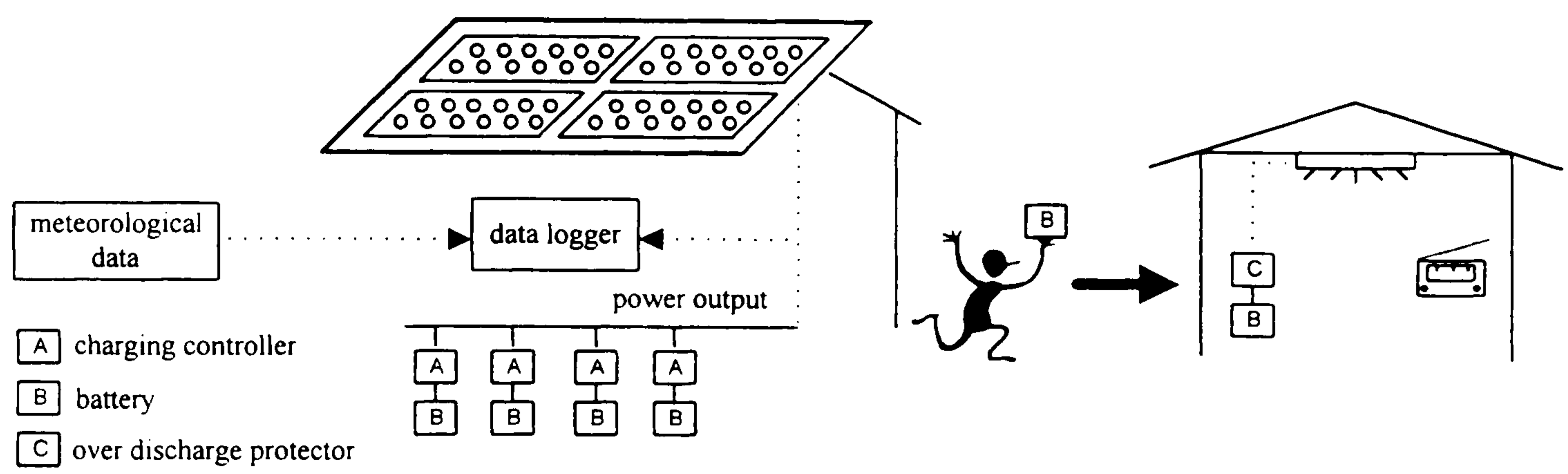


Figure 5.1 A typical PV battery charging station

The system is easy to install and requires low maintenance. However, when assessing the economic viability of the PV battery charging compared to its alternatives, the associated operational and maintenance cost should be considered as well as capital cost and relative output. These will vary considerably for each site and application. When comparing systems from alternative supplies, it is necessary to look at array and battery size, charge rate specified for a given level of solar insolation and which components are supplied with the system [1]. Reliability is an important factor as electronic controls have proven the least reliable part of many PV systems. Lessons learned from using PV battery charging stations have been reported [2-4], most problems were technical and charge controller problems.

5.2.1 Design of a PV Battery Charging Station System in the Sample Village

The PV system sizing for a BSC will depend greatly on the following parameters (i) number of battery charging points, which should be sufficient to avoid long queues, (ii) the local solar insolation, (iii) total ampere-hours load used for batteries needing to be charged. The general design is to calculate the total number of modules used based on the significant parameters above including the I-V characteristics of a PV module. Table 5.1 provides a sample load in each household (from the loads for each household in Table 4.3). The design give a sample of a system intended to charge a maximum of twenty-five batteries per day, i.e., the number of charging points is also twenty-five.

Table 5.1 Daily load requirement in each household of the sample village at Udon Thani of Thailand

Appliances	Power (W)	Hours used/day
Radio	10	2
Fluorescent (small)	8	3
Fluorescent (medium)	18	6

The daily load requirement given above is the same daily load demand in the case of a centralised PV mini-grid system. The system requires the power for charging a battery which is to be discharged for 4 days on an energy need basis and a maximum depth of discharge of 70%. In fact, the number of days that the battery is used is one of the main factors to estimate the number of modules per charging point. Similarly, the number of charging points also directly affects system sizing. Furthermore, a fairly sophisticated load control system is required to regulate the charging of each of the batteries separately. It is strongly recommended that an over-discharge protector should be installed in each household to protect the battery from over-discharging.

GENERAL CONSIDERATIONS

Application :	Battery Charging Station
Site :	Udon Thani, Thailand
Location :	17.3° N, 102.8° E
Environment :	High Plains
Maximum Wind speed :	5.9 m/s (at 600 m height)
Load :	Batteries

ARRAY :
The array azimuth should be true south with tilt angle. PV array should be located close to the loads or batteries to reduce power loss. The array frame should be grounded. Array should be wired in series first to obtain proper voltage. Series strings should then be wired in parallel to obtain the current required for charging batteries. Array sizing depends mainly on the solar insolation at the design location and number of charging points.

CONTROLLER : The charge regulator is a very important part for a PV battery charging system to prevent deep discharge and overcharge of the battery. Lessons learned have been indicated that most used batteries that need to be charged are deeply discharged. As a result, the battery lifetime could be reduced significantly or battery damaged unexpectedly. It is recommended that a voltage regulator must be installed in each household to prevent deep discharge of the battery. Furthermore, the voltage regulators must also be normally mounted at the charging station to prevent overcharge of the batteries.

BATTERIES :
The battery type for users to use in each household, deep cycle lead-acid type specifically designed is recommended because it is widely available in many rural shops of Thailand. If liquid electrolyte batteries are used, nonmetallic enclosures are recommended to prevent corrosion. Users must abide by users' manual carefully, especially maintenance of battery.

INVERTER :

Due to the fact that the load is a DC unit (battery), then the system does not need an inverter.

LOAD :
In the case of a PV battery charging system, its load is a battery that the user transports from home to the charging station and picks up when it is fully charged. Some battery types cannot accept a full charge after being left in a low state of charge for a long period, they have been further harmed by overcharging. In this case, it is confirmed that a charging controller must be installed in each household in which the battery is being used.

WIRING/SWITCH GEAR :
The cable sizes and types wired from the charging controllers to batteries (loads) in the charging station should be selected corresponding to its duty. In fact, cable type (THHN) for battery wiring is recommended. All wiring, fusing should conform to standard electrical procedure. Selecting a suitable size of fuse is critical to protect all system components from damage due to short circuit current or over current flows.

MOUNTING :
PV arrays can be designed to be mounted on the charging station's roof. However, they can also be mounted on the ground and that is recommended because it is very easy to access for maintenance and the capital cost of installation will be reduced. Array frames should be anodized aluminium, galvanized or stainless steel and designed for maximum anticipated wind velocities. Grounding systems should be mounted to prevent leakage and surge currents from all equipment and lightning strike respectively.

Worksheet #1	Calculation of the daily load demand												
Load description	DC or AC	No. of sets	Load current (A)	Load voltage (V)	DC power (W)	AC power (W)	Daily duty cycle (h/day)	Weekly duty cycle (d/week)	7 days in a week	Power conversion eff. (decimal)	Energy requirement (Wh/day)	Nominal system voltage (V)	Ampere hour load (Ah/day)
			×	×	=	=	×	×	÷	×	=	÷	=
Radio	*DC*	*1*	*0.84*	*12*	*10*	*N/A*	*2*	*7*	*7*	*1*	*20*	*12*	*1.67*
Fluorescent 8 w	*DC*	*1*	*0.8*	*12*	*9.6*	*N/A*	*3*	*7*	*7*	*1*	*28.8*	*12*	*2.40*
Fluorescent 18 w	*DC*	*1*	*1.8*	*12*	*21.6*	*N/A*	*6*	*7*	*7*	*1*	*129.6*	*12*	*10.80*
				Total DC load power (W)	***41.2***	***N/A***	**Total AC load power (W)**			**Total Wh/day**	***178.4***	**Total Ah/day**	***14.86***

Design Notes

1) These loads are used **in** *each household per day.*

2) Both wattage sizes of lamp are widely available in many rural areas in Thailand.

Maximum Tilt Angle Worksheet # 2	**Estimate The Maximum Tilt Angle (for Battery Charging Station)**

Site : *Udon Thani of Thailand* **Latitude :** *17.38 °N* **Longitude :** *102.72 °E*

Month	Ampere-hours load (Ah/day)		Peak sun (h/day)		Current (A)	Select the largest current and corresponding peak sun	
Tilt at latitude - 25°							
Jan.	*14.86*	÷	*5.773*	=	*2.57*		
Feb.	*14.86*	÷	*4.780*	=	*3.10*		
Mar.	*14.86*	÷	*3.969*	=	*3.74*		
Apr.	*14.86*	÷	*4.105*	=	*3.62*		
May	*14.86*	÷	*3.392*	=	*4.38*	latitude - 25°	
Jun.	*14.86*	÷	*3.508*	=	*4.23*	peak sun	current
Jul.	*14.86*	÷	*3.166*	=	*4.69*	(h/day)	(A)
Aug.	*14.86*	÷	*3.233*	=	*4.59*	*3.166*	*4.69*
Sep.	*14.86*	÷	*4.003*	=	*3.71*		
Oct.	*14.86*	÷	*4.543*	=	*3.27*		
Nov.	*14.86*	÷	*4.898*	=	*3.03*		
Dec.	*14.86*	÷	*5.400*	=	*2.75*		
Tilt at latitude							
Jan.	*14.86*	÷	*5.317*	=	*2.79*		
Feb.	*14.86*	÷	*4.737*	=	*3.13*		
Mar.	*14.86*	÷	*4.246*	=	*3.50*		
Apr.	*14.86*	÷	*4.714*	=	*3.15*		
May	*14.86*	÷	*4.105*	=	*3.62*	latitude	
Jun.	*14.86*	÷	*4.407*	=	*3.37*	peak sun	current
Jul.	*14.86*	÷	*3.859*	=	*3.85*	(h/day)	(A)
Aug.	*14.86*	÷	*3.773*	=	*3.94*	*3.773*	*3.94*
Sep.	*14.86*	÷	*4.409*	=	*3.37*		
Oct.	*14.86*	÷	*4.617*	=	*3.22*		
Nov.	*14.86*	÷	*4.642*	=	*3.20*		
Dec.	*14.86*	÷	*4.918*	=	*3.02*		
Tilt at latitude + 25°							
Jan.	*14.86*	÷	*4.104*	=	*3.62*		
Feb.	*14.86*	÷	*4.065*	=	*3.65*		
Mar.	*14.86*	÷	*4.001*	=	*3.714*		
Apr.	*14.86*	÷	*4.805*	=	*3.09*		
May	*14.86*	÷	*4.385*	=	*3.38*	latitude + 25°	
Jun.	*14.86*	÷	*4.856*	=	*3.06*	peak sun	current
Jul.	*14.86*	÷	*4.164*	=	*3.56*	(h/day)	(A)
Aug.	*14.86*	÷	*3.904*	=	*3.80*	*3.744*	*3.97*
Sep.	*14.86*	÷	*4.272*	=	*3.47*		
Oct.	*14.86*	÷	*4.089*	=	*3.63*		
Nov.	*14.86*	÷	*3.755*	=	*3.95*		
Dec.	*14.86*	÷	*3.744*	=	*3.97*		

	peak sun (h/day)	current (A)
Now select the latitude angle that give the smallest current and corresponding peak sun from each latitude and enter on the right hand side	*3.773*	*3.94*
	Max. tilt angle selected	
Note : This angle is for fixed tilt angle throughout the year	*17°*	

Design Notes :

Battery Charging Station Worksheet # BCS	PV System Sizing of Battery Charging Station
Site : *Udon Thani of Thailand* Array tilt angle : *17* Degrees Monthly mean daily solar radiation : *3.77* kWh/m^2	The worst month of the year : *August* Number of charging points required : *25* Availability required : *Non-Critical Design*

1) PV Array Sizing

Ampere-hours load (Ah/day)		Regulator efficiency (decimal)		Battery efficiency (decimal)		Line loss factor (decimal)		Corrected ampere-hours (Ah day)
14.86	÷	*0.85*	÷	*0.85*	÷	*0.95*	=	*21.65*

Corrected ampere-hours (Ah/day)		Peak sun hours at selected tilt angle (h/day)		Module degradation factor (decimal)		No. of days battery used (days)		Corrected array current (A)
21.65	÷	*3.77*	÷	*0.9*	×	*4*	=	*25.50*
						Rated current of a PV module (A)	÷	*4.72*
						No. of modules connected in parallel	=	*(5.4) ~ 5*

Nominal system voltage (V)		Nominal voltage of a PV module (V)		No. of modules connected in series		No. of modules connected in parallel		Total number of modules used per point
12	÷	*12*	=	*1*	×	*5*	=	*5*
						Number of charging points required	×	*25*
						Total number of modules used	=	*125*

2) Battery Sizing

Corrected ampere-hours (Ah/day)		Days of battery used (day)		Max. depth of discharge (decimal)		Corrected battery capacity (Ah)		Each battery capacity (Ah)		No. of batteries connected in parallel
21.65	×	*4*	÷	*0.7*	=	*123.71*	÷	*120*	=	*~ 1*

Nominal system voltage (V)		Nominal battery voltage (V)		No. of batteries connected in series		No. of batteries connected in parallel		Total number of batteries used
12	÷	*12*	=	*1*	×	*1*	=	*1*

PV module information		Battery information
Manufacturer : *BP Solar*		Manufacturer : *BP Solar*
Model : *BP 585 F*		Model : *L120*
Type : *monocrystalline silicon (36 series cells)*		Type : *Lad-Aid (Deep Cycle)*
SC current : *5* A	OC voltage : *22.3* V	Nominal voltage : *12* V
Max. current : *4.72* A_{mp}	Max. voltage : *18* V_{mp}	Rated capacity : *120* Ah

Design Notes :

1) *Number of modules connected in parallel in topic 1 is rounded down into 5 modules because availability required is non-critical design*
2) *Battery sizing in topic 2 means a capacity of battery that will be used in each household.*
3) *The PV battery charging station can provide the power of 10.62 kW_p*

Charge Controller General Worksheet # CC	Technical Specifications of Charge Controller

Short circuit current of a module (A)		No. of modules connected in parallel		Safety factor		Design controller capacity (A)		Each rated ampere of controller (A)		No. of controllers in parallel
5	×	*5*	×	**1.25**	=	*31.25*	÷	*30*	=	*~ 1*

Manufacturer : *BP Solar*
Regulator Type : *GCR3000(m)*
System voltage (V) : *12*
Maximum load current (A) : *30*
Operating temperature (°C) : *-25 °C to +50 °C*
Disconnection pre-warning : *SOC<40% (11.7 V)*
Disconnection level : *SOC<30% (11.1 V)*
Reconnection level : *SOC>50% (12.6)*

Metering and protection

Voltage : ✓❑ Yes ❑ No
Current : ✓❑ Yes ❑ No
State of Charge (SOC) : ✓❑ Yes ❑ No
Under and Overvoltage : ✓❑ Yes ❑ No
Over-temperature, load current : ✓❑ Yes ❑ No
Others : LED display for charge control and over-discharge protection

Design Notes :

1) Rating of regulator for this sheet is based on one charging point.
2) The total number of regulators used for this system is 25
3) It is recommended that a regulator must be installed in each household to protect the battery damage from over discharging.
As a result, sizing of a regulator in this example should be sized is as follows:
Model GGR800(m),
Max. current : 8 A

Protection of System Components General Worksheet # PSC	Protection of System Components

Array Description								
Short circuit current of a module (A)		No. of modules connected in parallel		Total array short circuit current (A)		Safety factor		Rated current of protective device (A)
5	×	*5*	=	*25*	×	**1.25**	=	*31.25*
Controller / Main Load Description								
Total DC load power (W)		Nominal system voltage (V)		Maximum DC load current (A)		Safety factor		Rated current of protective device (A)
	÷		=		×	**1.25**	=	*N/A*
Battery Description								
Maximum current of a module (A)		No. of modules connected in parallel		Peak current from PV array (A)		Safety factor		Rated current of protective device (A)
4.72	×	*5*	=	*23.6*	×	**1.25**	=	*29.5*
Inverter Description								
Total AC load power (W)		Nominal system voltage (V)		Power factor (decimal)		Safety factor		Rated current of protective device (A)
-	÷	-	÷	-	×	**1.25**	=	*N/A*

Branch Circuit # 1 (specify)					Branch Circuit # 2 (specify)				
Rated load current (A)		Safety factor		Rated current of protective device (A)	Rated load current (A)		Safety factor		Rated current of protective device (A)
-	×	**1.25**	=	*N/A*	-	×	**1.25**	=	*N/A*
Branch Circuit # 3 (specify)					**Branch Circuit # 4 (specify)**				
Rated load current (A)		Safety factor		Rated current of protective device (A)	Rated load current (A)		Safety factor		Rated current of protective device (A)
-	×	**1.25**	=	*N/A*	-	×	**1.25**	=	*N/A*

Circuit	Protective Device (No. of Devices)				Rated Current	Rated Voltage	Descriptions
	CB	Fuse	Switch	Surge	(A)	(V)	
Array to controller		*2*			*30*	*250*	*HRC fuse*
Controller to load			*1*		*30*	*250*	*DPST switch*

Design Notes:

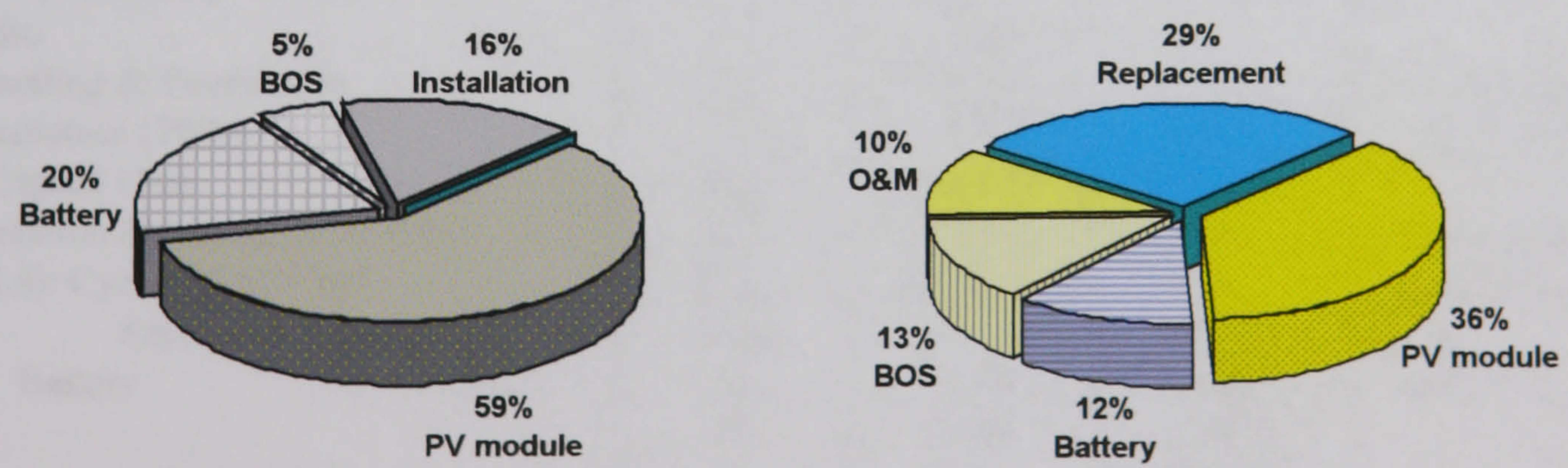
1) *It is a class R fuse and is cartridge fuse with breaking capacity 40 kA at 250 VDC including fuse holder rated 30 A for two fuses.*
2) *A double poles single throw switch for use in charging station per charging point.*
3) *Due to the fact that there are 25 charging points , then 25 sets of fuse and switch in 1 and 2 will be used in this system.*

DC Wring General Worksheet # DCW	DC Wire Sizing Specification				
Descriptions	System voltage (V)	Maximum current (A)	Allowable voltage drop (%)	Wire size (mm^2)	Wire type
Array Circuit					
Module to Module	*12*	*5*	*2*	*2.5*	*THW*
Array to Control Building					
Array to Controller / point	*12*	*30*	*2*	*4*	*THW*
DC Circuits					
Battery to Battery					
Battery Charger to Battery					
Battery to Inverter or Converter					
Regulator to battery / point	*12*	*30*	*2*	*6*[1]	*THHN (battery cable)*
Branch Circuit					
1. *N/A*					
2.					
3.					
4.					
5.					
System Grounding	Wire Size (mm^2)		Wire Type		Type of Earth Ground
Equipment Ground	-		-		-
System	*10*		*bare copper*		*to ground rod*

Design Notes:

1) *The minimum conductor size of battery must be ≥ 6 mm^2 and use specific cable type for wiring.*
2) *Wiring system is based on one charging point or unit.*
3) *The total number of charging points is 25.*

5.2.2 Life Cycle Cost Analysis of a PV Battery Charging Station



(a) Capital Cost of a Battery Charging Station System (b) Life Cycle Cost of a Battery Charging Station system

Figure 5.2 Cost elements of a battery charging station

Table 5.2 Life cycle cost analysis of a battery charging station

Project/Site : Udon Thani, Thailand		**Type of system :** PV battery charging station		
1. Financial parameters	*Symbol*	*Values*	*Unit*	*Remark*
Period of analysis	n	20	years	project lifetime
Discount rate	d	0.10		
Inflation rate	I	0.05		
Discount factor	a	0.954		$a = (1+i)/(1+d)$
Annualised factor	$P_{a(n)}$	12.65		$P_{a(n)} = a(1-a^n)/(1-a)$
2. System specification and performance				
Daily load	L_d	4.46	kWh/day	25 charging points
Annual load	L_a	1627.9	kWh/year	$365*L_d$
Solar Module				
Array size	S_a	10625	W_P	existing data
Module unit price	S_p	6	$/W_P$	silicon cells
Lifetime	S_{lt}	20	years	
Battery				
Battery capacity	B_c	144	kWh	100 sets
Battery unit price	B_p	150	$/kWh	
Lifetime	B_{lt}	5	years	
Controller				
No. of controllers used	R_t	25	sets	existing data
Charge controller unit price	R_p	70	$/sets	
Controller lifetime	R_{lt}	5	years	
End-user loads				
Fluorescent lamps 8 w		300	$	100 lamps
Fluorescent lamp 18 w		400	$	100 lamps
Lifetime		2	years	
Radio		3000	$	100 sets
Lifetime		10	years	
Mounting and Foundation				
Mounting & Foundation unit price	K_p	0.5	$/W_P$	
Lifetime	K_{lt}	20	years	
3. Cost data				
PV array	C_{pv}	63750	$	$C_{pv} = S_a * S_p$
Battery	C_{bat}	21600	$	$C_{bat} = B_c * B_p$
Charge controllers	C_{cc}	1750	$	$C_{cc} = R_t * R_p$
Fluorescent lamp 8 w		300	$	
Fluorescent lamp 18 w		400	$	
Radio		3000	$	
Mounting & Foundation	C_{sw}	5312.5	$	$C_{sw} = S_a * K_p$
Installation (20%)	C_{in}	12750	$	$C_{in} = 0.2*C_{pv}$
a) Capital Cost	C_{cap}	**108862.5**	$	
Operation & Maintenance (2%)	C_{om}	1275	$	$C_{om} = 0.02*C_{pv}$
b) Life Cycle O&M Cost	$C_{o\&m}$	**16128.75**	$	$C_{o\&m} = C_{om} * P_{a(n)}$
Replacement Cost	*Yr.(i)*		*PW*	
(i) Battery	5	0.79	17064	$PW = C_{bat} * P_{r(i)}$
	10	0.63	13608	
	15	0.5	10800	
(ii) Charge controllers			3360	every 5 years
(iii) Fluorescent lamp (8w + 18w)			4340	every 2 years
(iv) Radio			1890	every 10 years
c) Life Cycle Replacement Cost	C_{rep}		**51062**	
d) Salvage	C_{sal}		**-0.0**	
4. Economic indicator				
Total Life Cycle Cost	LCC	**176053.25 US$**		LCC = a+b+c-d
Annualised LCC	ALCC	**13917.25 US$/year**		ALCC = LCC/$P_{a(n)}$
Cost of Electricity	COE	**8.54 US$/kWh**		COE = ALCC/L_a

5.3 PV Pumping Systems

The use of a PV plant in water pumping systems for village water supply, livestock watering and irrigation purposes is advantageous for many aspects. PV pumping systems are used to pump the water from boreholes, open wells and canals to provide rural water supplies. The majority of the 10,000 or more pumping systems installed are used for village water supply and livestock watering [5]. The problems of use are resolved and experience suggests that poor performances are commonly caused by incorrectly specified solar and water resource including water demand data. However, water pumping has a long history so many methods have been developed to pump water with a minimum effect. These have utilised a variety of power resources, such as hand pumps, animal driven pumps, hydraulic pumps, wind pumps, diesel or gasoline engine pumps and solar pumping systems. The initial criteria for selecting a system in a typical rural area can be expressed in the simple decision flowchart that is shown in Figure 5.3.

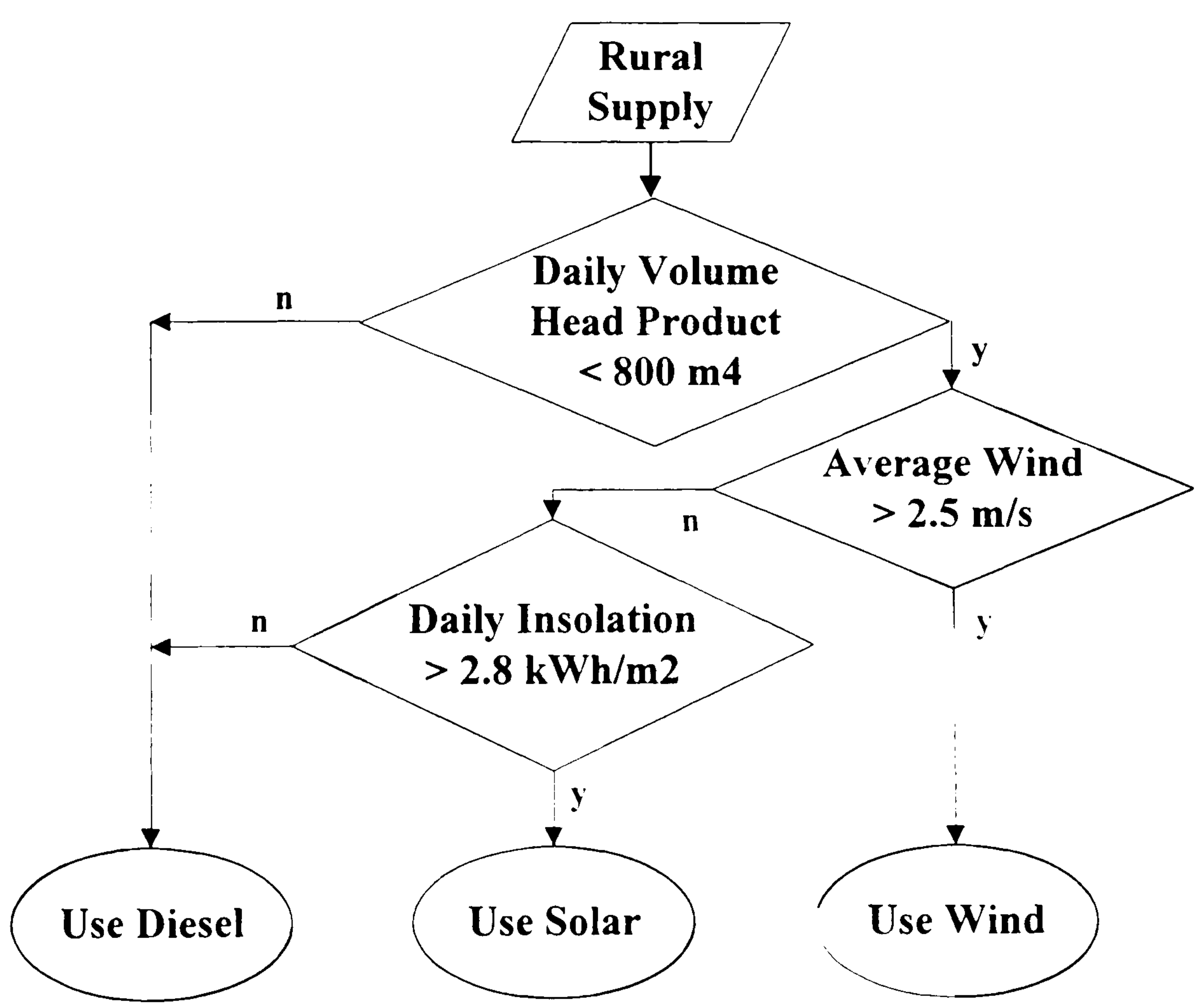


Figure 5.3 A decision chart for pumping in a typical rural area

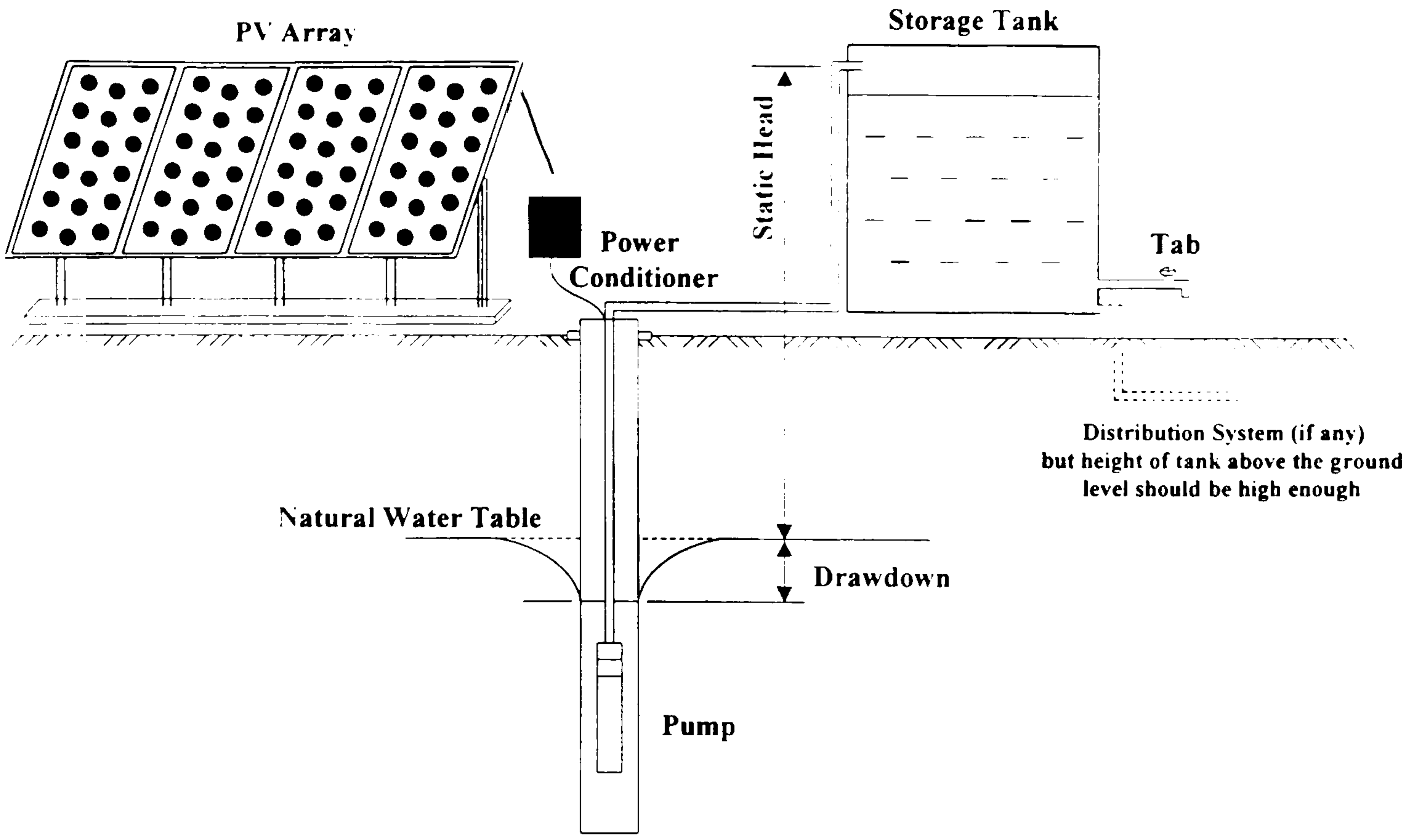


Figure 5.4 A typical PV pumping system for village water supply

Domestic water use per capita tends to very greatly depending on availability. The long term aim is to provide people with water in sufficient quantities to meet all their requirements for drinking, washing and sanitation. Present short term has a goal to aim for a per capita provision of 40 litres per day, thus a village of 500 people has a requirement of 20 m^3 per day [5-8]. As can be seen from Figure 5.4, for village water supply storage is essential, and should be adequate for several days of water supply. Although 5 days may be desirable, in practice only about 2 or 3 days is usually affordable. In environments where rainy seasons occur, the reduced output of the PV pump during these periods can be offset by rainwater harvesting. A typical example would be a central raised storage tank close to the pump (to minimise dynamic head losses) and a piped distribution system to stand-pipes. Accepted water engineering practice, where cheap energy is available, is to position the tank on a tower. However, PV pumps are typically used where either no distribution or only a few short branches to stand-pipes are required. The tank should be positioned high enough to provide only enough head necessary to carry water effectively through the distribution system. It must be remembered that array size and pump are proportional to head and that a higher tank level will increase the system cost. In this case the tanks should be wide and squat rather than tall. Generally, the height of tanks should not be over 2 metres.

The pipe is a cheaper part of the system, and can therefore be oversized to reduce dynamic losses to a minimum. The technologies of PV pumping systems are broadly configured into 5 types as shown in Figure 5.5 [5-7].

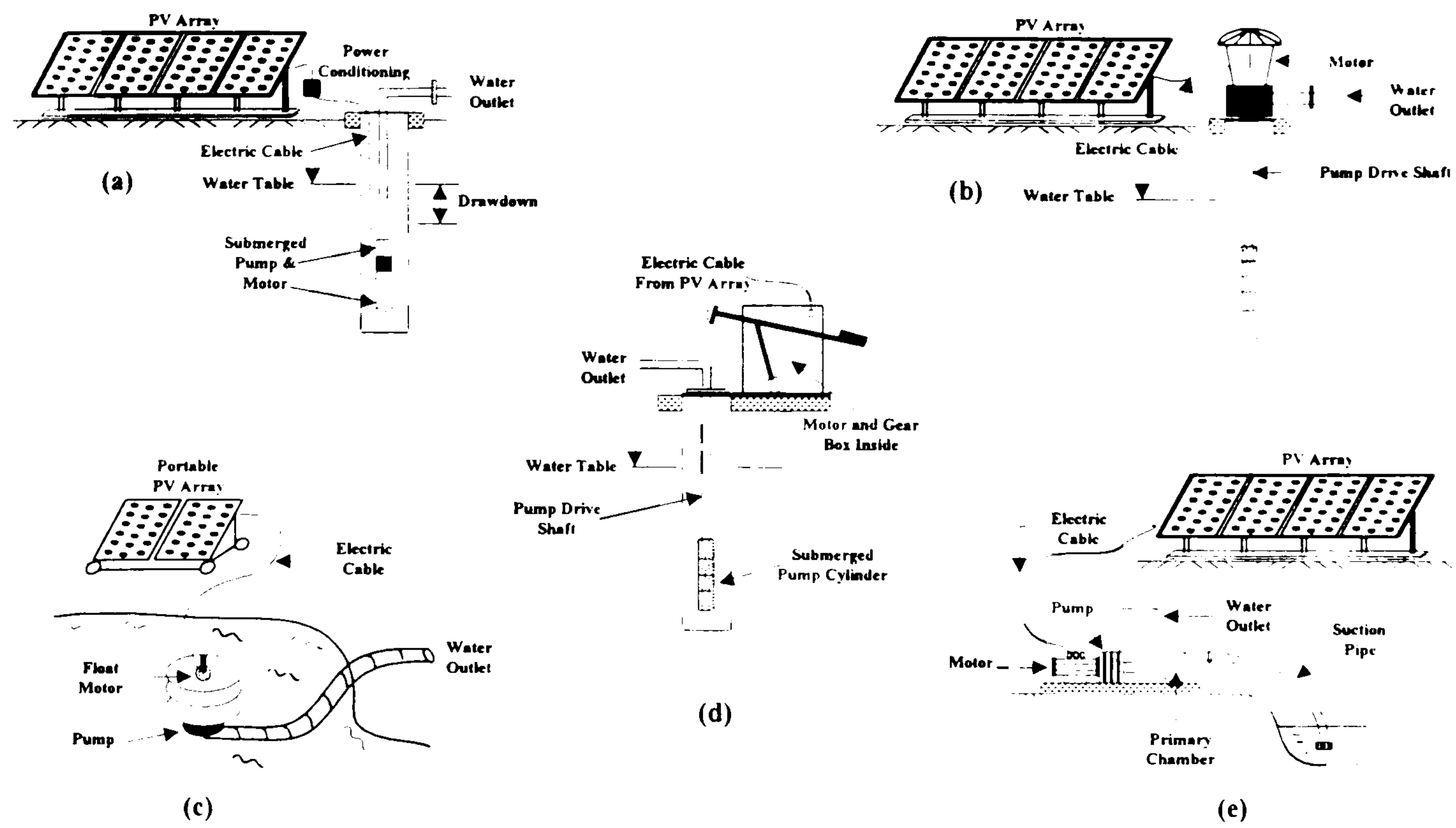


Figure 5.5 A various motor and pump-set configuration : (a) submerged motor/pump, (b) submerged pump/surface motor, (c) floating motor/pump, (d) jack pump-reciprocating positive displacement, (e) surface suction pump

(a) ***Submerged multistage centrifugal motor pump-sets*** : This type is probably the most common type of PV pump used for village water supply. This is easy to install (often with lay-flat flexible pipe work) and the motor pump-set is submerged away from potential damage. Both AC and DC pumps are available; an inverter must be needed for AC system. In the case of a brushed DC motor then the equipment will need to be pulled up from the well (around every 2 years) to replace brushes. If brushless DC motors are incorporated then electronic commutation will be required. However, the most commonly employed system consists of an AC pump and inverter with a PV array of less than 1.5 kW_P. The centrifugal pumps can be used for boreholes or open water resources, volumetric pumps are often used for deep wells. Wiring for submersible pumps must be a type approved for submersible pump applications. Heavy duty double insulated cable is suggested.

(b) ***Submerged pump with surface mounted motor*** : This type has been installed with turbine pumps in some developing countries. It gives easy access to the motor for brush changing and other maintenance. However, its low efficiency from power losses in the shaft bearing and the high cost of installation are disadvantages. Generally, this configuration is largely being replaced by the submersible motor and pump-set.

(c) ***Floating motor pump sets*** : The portability of the floating pump set makes it ideal for irrigation pumping from canals and open wells. The pump moves with the water level, and is not likely to run dry. The arrays are often mounted on wheels to allow easy movement. Obviously, this design is not suitable for borehole pumping.

(d) ***Reciprocating positive displacement pump*** : The output is proportional to the speed of the pump. At high head the frictional force is low compared with the hydrostatic forces, often making positive displacement pumps more efficient than centrifugal pumps for this case. Reciprocating positive displacement pump creates a cyclic load on the motor which needs to be balanced for efficient operation. Hence, the above ground components of the solar pump are often heavy and robust, and power controllers for impedance matching are normally used.

(e) ***Surface suction pump-set*** : This type is not generally used, due to self starting and priming problems, particularly at high suction heads. Although the physical limit on the suction head is about 8 metres, it is better to operate at the minimum possible. A pumping performance that is most suitable for a design condition in terms of system head and daily volume of water pumped can be found from Figure 5.6. It shows the typical ranges of different pump types as a function of output and head. The shading indicates the areas of the graph in which various configurations are most suitable, and can be used as a guideline with a technical performance appraisal. The axes of the graph are logarithmic. This is so that lines of constant volume-head product would be straight. If the performance range lines of the different pumps are drawn on a diagram of this kind, they would line in roughly the same direction as the constant volume-head product lines, but be somewhat curved. This illustrates the fact that the actual volume-head product varies across the range of pumping conditions for a given pump, reaching a peak somewhere in the middle of the range.

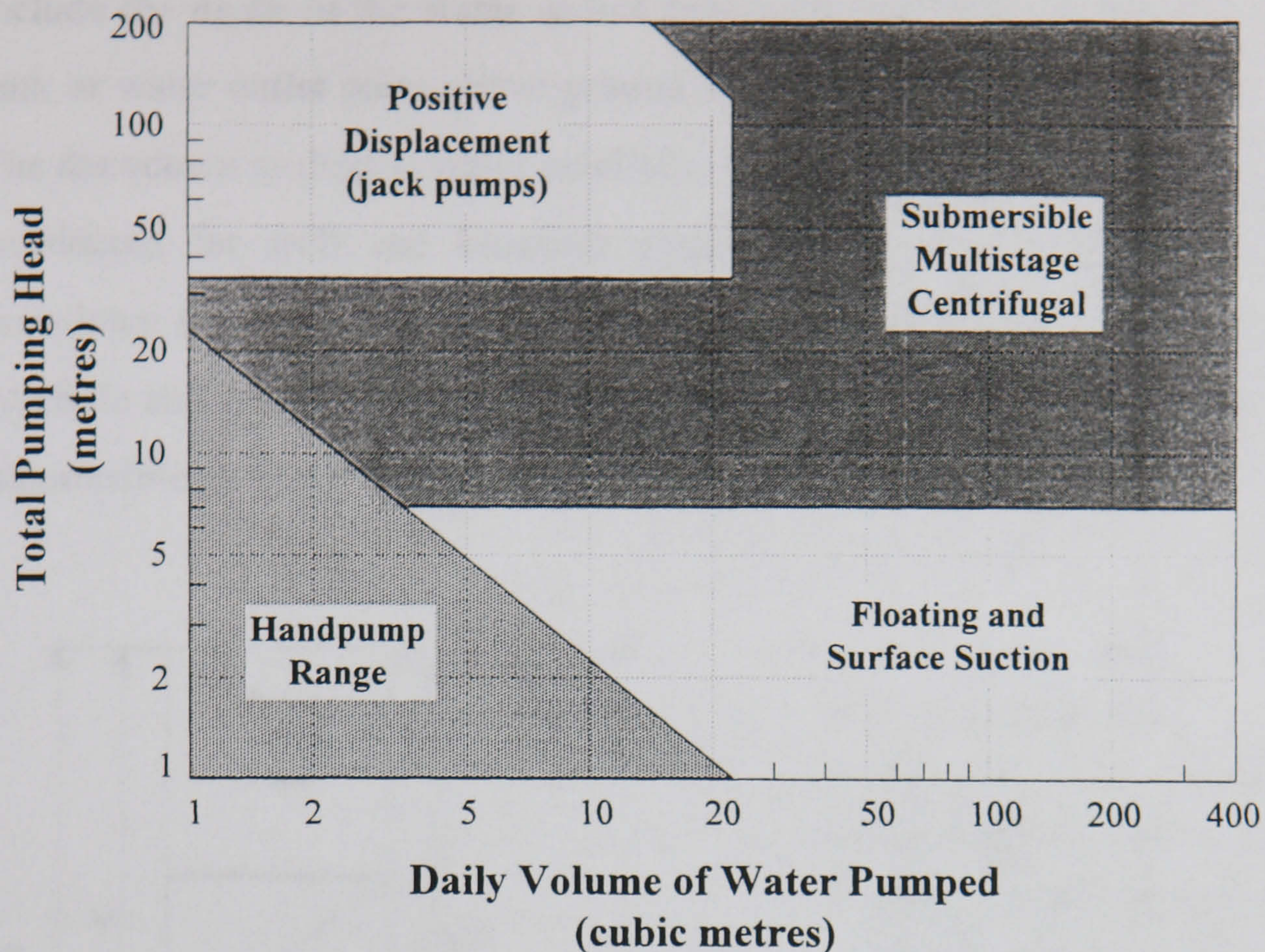


Figure 5.6 Configuration on various heads and volumes [8]

The typical systems of village water supply in the developing countries have an array rating of around 1 kW_P (for Thailand see topic 1.7). The village water supplies usually come from the boreholes (surface water should be avoided unless filtered due to probable contamination) with the head between 15 and 40 metres. The volume of water pumped is typically between 20 and 40 m^3/day. This corresponds to a domestic water supply for the villages of between 500 and 1000 people respectively. The World Health Organization (WHO) surveyed this in 1970 and has shown that the average per capita water consumption in developing countries ranges from 35 to 90 litres per day. The WHO subsequently defined 40 litres per day as a short term goal for the developing world. It means that 500 people in a village need water consumption up to 20 m^3/day. This covers drinking water, washing, cooking and sanitation needs.

5.3.1 Design of a PV Pumping System for Village Water Supply

There are three main parameters which concern the estimation of pumping system sizing, namely volume of water requirement (m^3/day), total hydraulic head (m) and solar resource at design location (kWh/m^2/day). Furthermore, some water resource parameters need to be taken into account, and measured if possible. These parameters include the depth of the water source below ground level, the height of the storage tank or water outlet point above ground level and seasonal variations of water level. The drawdown or drop in water level after pumping is also of concern and needs to be considered for well and borehole supplies. The exact relationship between the drawdown and the pumping rate will depend on the diameter and total depth of the borehole and the permeability of the rock and soil. The key parameters for a typical submersible pumping system can be illustrated in Figure 5.7.

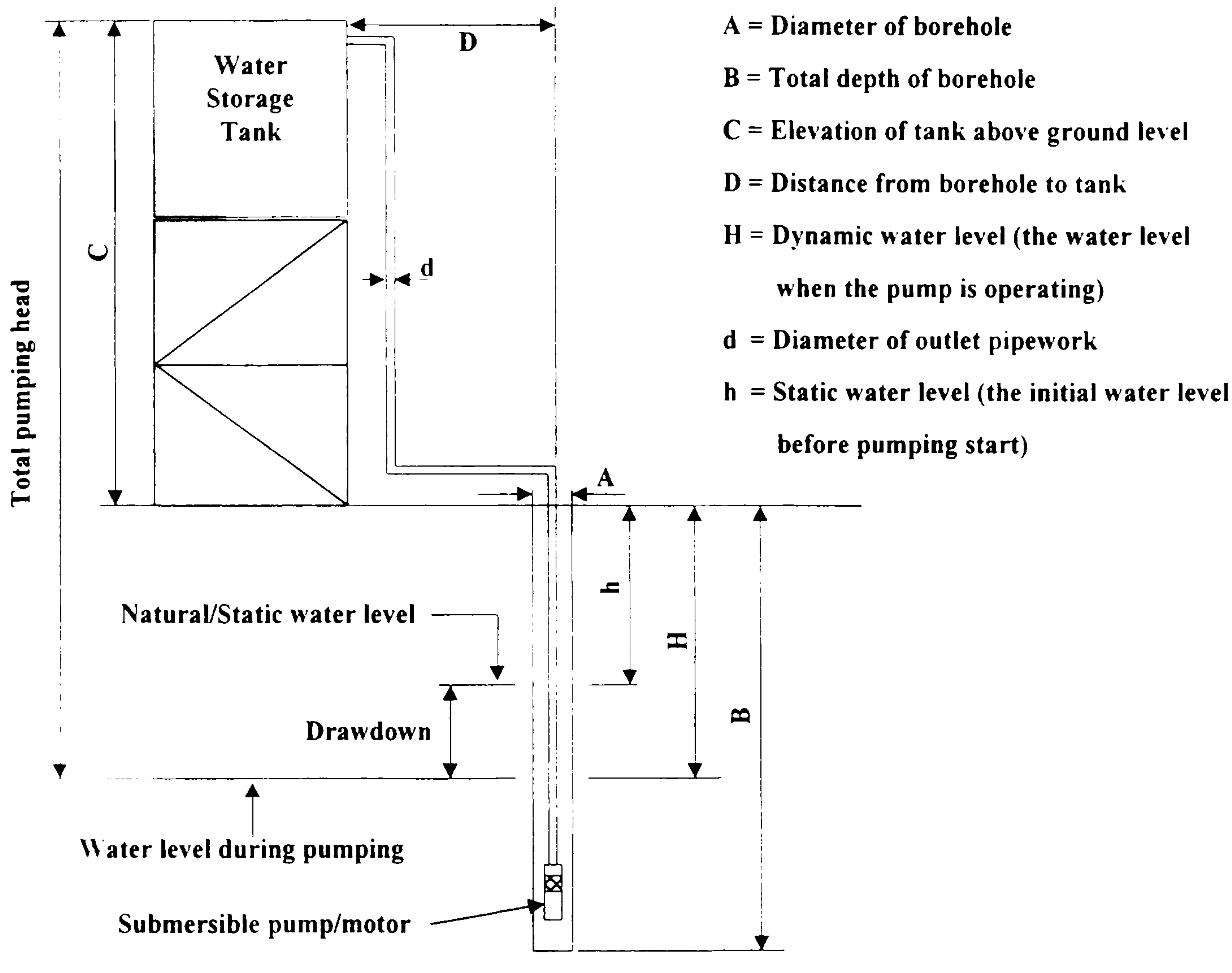


Figure 5.7 Key parameters for a typical submersible pumping system in rural village.

The first step of the design of a PV pumping system is to determine the energy requirement for pumping needs. The energy used for lifting a certain amount of water is called hydraulic energy. It is directly proportional to both the volume of water pumped expressed in cubic metres (m^3) and the total pumping head expressed in metres (m). The hydraulic energy is given by

$$E_h = \frac{(\rho_w . g . H . V_w)}{(3.6 \times 10^6)} \tag{5.1}$$

where

E_h = hydraulic energy required (kWh/day)

ρ_w = density of water (1000 Kg/m^3)

g = gravitational acceleration (9.81 m/s^2)

H = total pumping head (m)

V_w = volume of water required (m^3/day)

$$\frac{(\rho_w \cdot g)}{(3.6 \times 10^6)} = \frac{(9.81 \times 1000)}{(3.6 \times 10^6)} = 0.002725 = \frac{1}{367}$$

Thus, Equation 5.1 can be rewritten as

$$E_h = \frac{(H . V_w)}{367} \tag{5.2}$$

The quantity of volume per day that is multiplied by the total pumping head is called "the volume-head product", and its unit is m^4/day. The electrical power supplied by a PV generator depends on solar irradiation and subsystem daily energy efficiency (expressed as a fraction). PV system can be optimised from the mathematical relationships of the input-output of solar irradiation, PV generator and motor/pump subsystems. The PV array size required for pumping system can be expressed as follows:

$$W_a = \frac{(1000 \times V_w . H)}{(367 \times I \times \eta_S)} \tag{5.3}$$

where

W_a = array size expressed in Watts

I = daily solar irradiation on tilted surfaces expressed in kWh.m^{-2}.day^{-1}

η_S = pumping subsystem efficiency expressed as a fraction

Using the relationships above, a sample nomogram can be developed at various solar irradiation and pumping subsystem efficiencies as shown in Figure 5.8

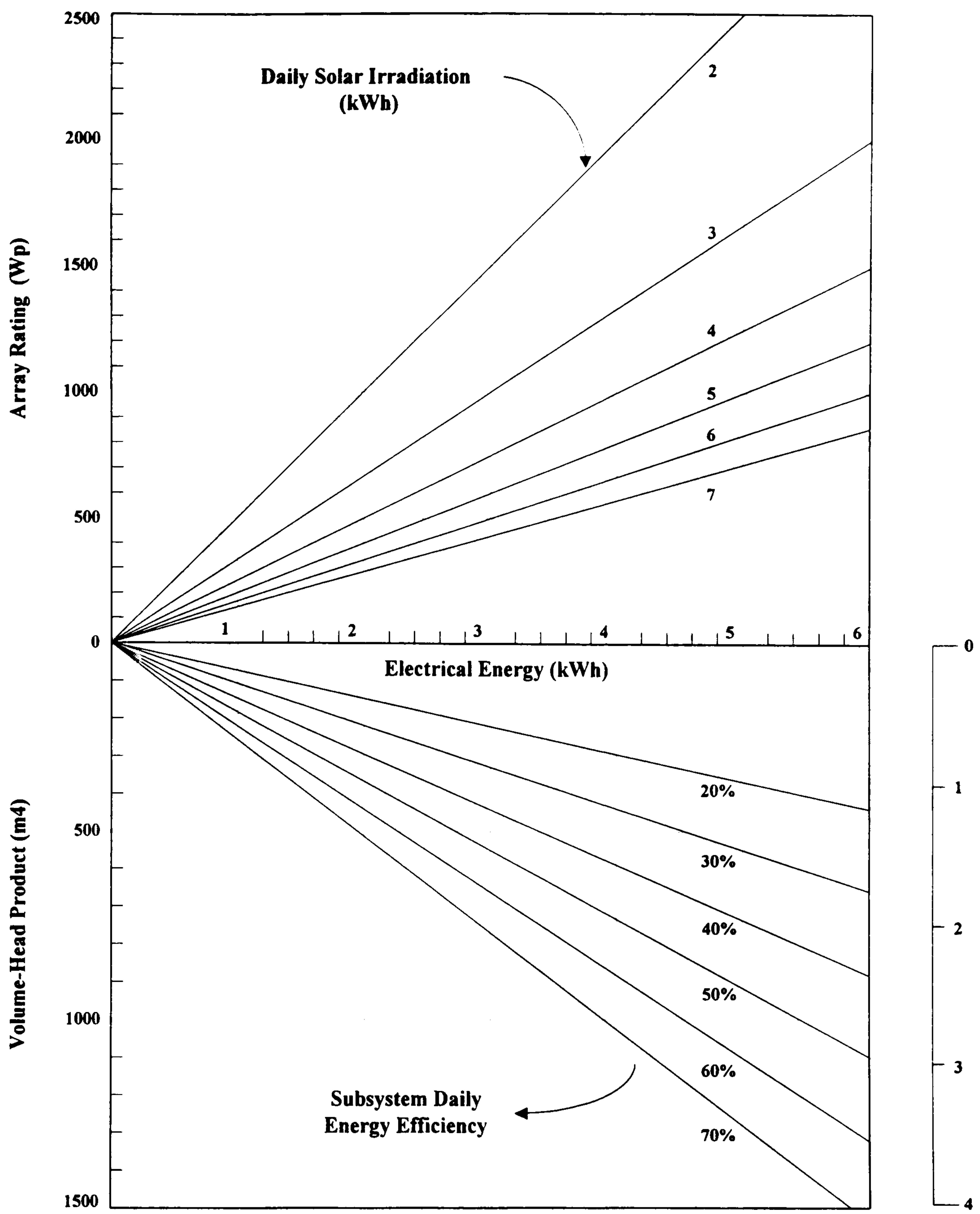


Figure 5.8 Nomogram for PV array rating [8]

As a result, a PV pumping system at the sample village with 100 households (500 people estimated, see topic 4.2.2) at Udon Thani of Thailand can be designed as follows:

GENERAL CONSIDERATIONS

Application :	Village Water Supply
Site :	Udon Thani, Thailand
Location :	17.3° N, 102.8° E
Environment :	High Plains
Maximum Wind speed :	5.9 m/s (at 600 m height)
Load :	AC submersible pump

ARRAY : The array azimuth should be true south with tilt angle. Array should be wired in series first to obtain proper voltage. Series strings should then be wired in parallel to obtain the current required for operation of the pumping load. A fused disconnect or circuit breaker in a rain proof enclosure should be installed at the array. Wiring must be a heavy duty type of cable with all connections in water-tight junction boxes with strain relief connectors. Use PVC conduits for output wiring to the well or the regulator.

CONTROLLER :

Water level switches or pressure switches may be needed to control water pumping. Constant voltage or maximum power tracking can significantly improve performance. Their price and lower reliability must be weighed against increased water production.

BATTERIES :

This is a direct-couple pumping system with no batteries required. The possibility of storing the pumped water in a tank eliminates the need for batteries in the system.

INVERTER :

The inverter can be selected from single or three phase depending on the type of motor/pump used. Basically, it must be designed to convert the DC voltage produced by a PV array into AC voltage with a variable frequency. The voltage's waveform must be pure sine wave that is strongly recommended to be used in the PV pumping system.

LOAD :

Manufactures of AC submersible pump will be able to recommend the proper pump/motor and array combination to meet water requirements at a site. For a direct coupled system, a tracking support structure will provide grater early morning and late afternoon current which can initiate early pump operation and increase water production.

WIRING/SWITCH GEAR :

Wiring for submersible pumps must be a type approved for submersible pump applications. Heavy duty double insulated cable is suggested. Since PV power pumps operate at low voltages, cable size must be carefully selected to keep wiring losses to less than 2-5%. Splicing of motor leads to output cable should utilize crimp-on connectors with resin filled heat shrink tubing or equivalent method to ensure long lasting, dry connection.

MOUNTING :

Average wind velocity must be taken into account when considering the use of a tracking support structure, as velocities above 25 miles/hours or 11.10 m/s may prevent accurate tracking. A ground mounted fixed or tracking support structure is commonly used for PV pumping systems. Location close to the borehole or the well is very important to keep wire length to a minimum. Fencing may be required to protect the array damage from unauthorised access.

Water Pumping Worksheet # 1 WP	**Calculation of the Water Pumping Load**

Application : *Village Water Supply* Site : *Udon Thani, Thailand* Location : *17.3° N*	Source water capacity : *6500* litres/hour Water volume required : *20* m^3/day Day of autonomy : *N/A* days Availability required : *Critical Design*

1) Total Pumping Head

Static water level (m)		Drawdown level (m)		Static lift level (m)		Static head level (m)		Friction loss (decimal)		Static head level (m)		Total pumping head (m)
19	+	*2*	+	*6*	=	*27*	×	*0.02*	+	*27*	=	*27.54*

2) Hydraulic Energy

Water volume required (m^3/day)		Total pumping head (m)		Volume-head product (m^4/day)		Conversion factor		Hydraulic energy (Wh/day)
20	×	*27.54*	=	*550.8*	÷	**0.367**	=	*1500.8*

3) Total Pumping Subsystem Efficiency

Motor/pump efficiency (decimal)		Battery efficiency (decimal)		Inverter efficiency (decimal)		Line loss factor (decimal)		Module degradation (decimal)		Total pumping subsystem efficiency (decimal)
0.50	×	*1.0*	×	*0.85*	×	*0.95*	×	*0.90*	=	*0.36*

4) Array Pumping Load

Hydraulic energy (Wh/day)		Total pumping subsystem efficiency (decimal)		Electrical energy (Wh/day)		Nominal system voltage (V)		Ampere-hours load (Ah/day)
1500.8	÷	*0.36*	=	*4168.8*	÷	*120*	=	*34.7*

Water Pump and Motor Information	**Notes**
Pump Type : *Multistage centrifugal pump* Manufacturer : *GRUNDFOS* Motor type : *Submersible motor* Motor Model : *MS 402* Power : *550 W* Input Voltage (AC) : *3×65 V, 50 H_z* Mean Pump/Motor Efficiency : *50* %	✱ If the pumping system has no battery and/or electronic controller, then enter a value of efficiency of 1.0 and sheet # 2 WP in the topic 2 (battery -sizing) does not need to be completed for system without battery back up.

Design Notes :

This system is designed for using a 3-phase inverter to convert the DC voltage (120 VDC) produced by a PV array into three phase AC voltage with a variable frequency.

Maximum Tilt Angle Worksheet # 2	Estimate The Maximum Tilt Angle (for PV Pumping System)

Site : *Udon Thani of Thailand* **Latitude :** *17.38 °N* **Longitude :** *102.72 °E*

Tilt at latitude - 25°

Month	Ampere-hours load (Ah/day)		Peak sun (h/day)		Current (A)
Jan.					
Feb.					
Mar.	*34.7*	÷	*3.969*	=	*8.7*
Apr.	*34.7*	÷	*4.105*	=	*8.4*
May	*34.7*	÷	*3.392*	=	*10.2*
Jun.					
Jul.					
Aug.					
Sep.					
Oct.					
Nov.					
Dec.					

Select the largest current and corresponding peak sun

latitude - 25°	
peak sun (h/day)	current (A)
3.392	*10.2*

Tilt at latitude

Month	Ampere-hours load (Ah/day)		Peak sun (h/day)		Current (A)
Jan.					
Feb.					
Mar.	*34.7*	÷	*4.246*	=	*8.1*
Apr.	*34.7*	÷	*4.714*	=	*7.3*
May	*34.7*	÷	*4.105*	=	*8.4*
Jun.					
Jul.					
Aug.					
Sep.					
Oct.					
Nov.					
Dec.					

latitude	
peak sun (h/day)	current (A)
4.105	*8.4*

Tilt at latitude + 25°

Month	Ampere-hours load (Ah/day)		Peak sun (h/day)		Current (A)
Jan.					
Feb.					
Mar.	*34.7*	÷	*4.001*	=	*8.6*
Apr.	*34.7*	÷	*4.805*	=	*7.2*
May	*34.7*	÷	*4.385*	=	*7.9*
Jun.					
Jul.					
Aug.					
Sep.					
Oct.					
Nov.					
Dec.					

latitude + 25°	
Peak sun (h/day)	current (A)
4.001	*8.6*

Now select the latitude that give the smallest current and corresponding sun peak from each latitude and enter on the right hand side
Note : This angle is for fixed tilt angle throughout the year

peak sun (h/day)	current (A)
4.105	*8.4*
Max. tilt angle selected	
17°	

Design Notes :

March, April and May are the dry months of the year at the design location when the water demand of 20 m^3/day is required. May is found to be the design month.

Water Pumping Worksheet # 2 WP	**Calculation of Array Sizing Installed and Battery Sizing**

Electrical energy (Wh/day)		Peak sun hours at selected tilt angle (h/day)		Array rating estimated (W_P)		Peak power of a PV module used (W_P)		No. of modules used
4168.8	÷	*4.10*	=	*1016*	÷	*70*	=	*(14.5) ~ 15*

1) Max. PV Array Sizing Installed

Nominal system voltage (V)		Nominal voltage of a PV module (V)		No. of modules connected in series	No. of modules used		No. of modules connected in series		No. of modules connected in parallel
120	÷	*15*	=	*8*	*15*	÷	*8*	=	*(1.88) ~ 2*

No. of modules connected in parallel		Maximum current of a PV module (A)		No. of modules connected in series		Maximum voltage of a PV module (V)		Array sizing installed (W_P)
2	×	*4.16*	×	*8*	×	*17*	=	*1130*

2) Battery Sizing

Electrical energy (Wh/day)		Nominal system voltage (V)		Corrected ampere-hour (Ah/day)		Day of autonomy (days)		Max. depth of discharge (decimal)		Corrected battery capacity (Ah)
-	÷	-	=	-	×	-	÷	-	=	-
								Each battery capacity (Ah)	÷	-
								No. of batteries connected in parallel	=	*N/A*

Nominal system voltage (V)		Nominal battery voltage (V)		No. of batteries connected in series		No. of batteries connected in parallel		Total no. of batteries used
-	÷	-	=	-	×	-	=	*N/A*

PV Module Information	**Battery Information**
Manufacturer : *BP Solar* Model : *BP270* Type : *Monocrystalline Silicon* Open Circuit Voltage (V) : *21.40* Short Circuit Current (A) : *4.48* Peak Voltage (V_{MP}) : *17.0* Peak Current (A_{MP}) : *4.16* Peak Power (W_P) : *70*	Manufacturer : *N/A* Model : *N/A* Type : *N/A* Nominal Voltage (V) : *N/A* Capacity (Ah) : *N/A*

Design Notes :

1) *Due to the fact that the batteries have not been used in this system, Hence, battery sizing in topic 2 does not need to be completed and skip into worksheet # 3WP.*

Water Pumping Worksheet # 3 WP	Calculation of Peak Water Flow Rate

Array sizing installed (W_P)		Total pumping subsystem efficiency (decimal)		Hydraulic power (W)		Conversion factor		Total pumping head (m)		Peak water flow rate (litres/hour)
1130	×	*0.36*	=	*406.8*	×	**367**	÷	*27.54*	=	*5421*

Peak water flow rate (litres/hour)	compared with	Source water capacity (litres/hour)
5421		*6500*

Does peak water flow rate exceed source capacity?

✓☐ **NO**	☐ **YES**
PV pumping system designed is suitable for operating in this case.	**See Notes**

: Notes :

If peak water flow rate is grater than source water capacity, consider the following options:

1) Reduce water volume required and consider a battery storage subsystem to operate during night time or low insolation. Then, recalculate the design.
2) Develop a water resource capacity.

Design Notes:

Power Conditioning General Sheet # PC				Power Conditioning Unit Specification Sheet			
Total AC power load (W)		Power conversion efficiency (decimal)		Safety factor		Minimum inverter size wattage (W)	Round up to next inverter size (W)
550	÷	*0.85*	×	**1.25**	=	*808.82*	*1000*

Inverter

Manufacture : *GRUNDFOS*
Inverter model no. : *SA 1500*
Output waveform : *Sine Wave with a Variable Frequency*
Nominal input voltage (VDC) : *120*
Output voltage (VAC) : *3x65 (3 phase)*
Frequency regulation (H_Z) : *50*
Nominal power (W) : *1500*
Efficiency (%) : *96 (Max)*

Design Notes :
This inverter type is specially designed to power submersible pumps installed in GRUNDFOS solar pumping system. It has a variety of application specific options (1500 w max.) and protects the pump against dry-running.

Converter

System Requirement		
Input DC voltage :	*N/A*	VDC
Output DC voltage :	*N/A*	VDC
Output power :	*N/A*	W
Converter Designed		
Manufacturer :		
Model :		
Input voltage :		VDC
Output voltage :		VDC
Output current :		A

1) There is no DC-DC converter in this system.

Protection of System Components General Worksheet # PSC	**Protection of System Components**

Array Description

Short circuit current of a module (A)	No. of modules connected in parallel	Total array short circuit current (A)	Safety factor	Rated current of protective device (A)
4.48	× *2*	= *8.96*	× **1.25**	= *11.2*

Controller/ Main Load Description

Total DC load power (W)	Nominal system voltage (V)	Maximum DC load current (A)	Safety factor	Rated current of protective device (A)
-	÷ -	= -	× **1.25**	= *N/A*

Battery Description

Maximum current of a module (A)	No. of modules connected in parallel	Peak current from PV array (A)	Safety factor	Rated current of protective device (A)
-	× -	= -	× **1.25**	= *N/A*

Inverter Description

Total AC load power (W)	Nominal system voltage (V)	Power factor (decimal)	Safety factor	Rated current of protective device (A)
-	÷ -	÷ -	× **1.25**	= *15*[1]

Branch Circuit # 1 (specify)			Branch Circuit # 2 (specify)		
Rated load current (A)	Safety factor	Rated current of protective device (A)	Rated load current (A)	Safety factor	Rated current of protective device (A)
	× **1.25**	= *N/A*		× **1.25**	= *N/A*
Branch Circuit # 3 (specify)			**Branch Circuit # 4 (specify)**		
Rated load current (A)	Safety factor	Rated current of protective device (A)	Rated load current (A)	Safety factor	Rated current of protective device (A)
	× **1.25**	=		× **1.25**	=

Circuit	Protective Device (No. of Devices) CB	Fuse	Switch	Surge	Rated Current (A)	Rated Voltage (V)	Descriptions
Array to inverter			*1*		*15*	*250*	*DPST*[2]
Inverter to load 3ϕ		*3*			*15*	*250*	*HBC*[3]

Design Notes:

1) *Maximum AC load current comes from the manufacturer's electrical data.*
2) *A double pole single throw switch with high breaking capacity (HBC) fuses.*
3) *It is a class R fuse and is cartridge fuse with high breaking capacity 40 kA at 250 VDC including fuse holder rated 30 A for two fuses. These fuses must be delay cutting type suitable for motor protection.*

AC wiring General Worksheet # ACW	AC Wire Sizing Specification				
Description	System voltage (V)	Maximum current (A)	Allowable voltage drop (%)	Wire size (mm^2)	Wire type
AC Circuit					
Inverter to AC load	*120*	*8.8*[1]	*3*	*2.5*	*THW*
AC Power Distribution line					
Branch Circuit					
1. *N/A*					
2.					
3.					
4.					
5.					
System Grounding	Wire Size (mm^2)		Wire Type		Type of Earth Ground
Equipment Ground	*6*		*bare copper*		*to ground rod*
system	-		-		-

Design Notes:

1) Maximum current of motor/pump from manufacturer's data.
2) The minimum size of cable must be ≥ 2.5 mm^2 for general installation.
3) For grounding system must be ≥ 6 mm^2.

DC Wring General Worksheet # DCW	DC Wire Sizing Specification				
Descriptions	System voltage (V)	Maximum current (A)	Allowable voltage drop (%)	Wire size (mm^2)	Wire type
Array Circuit					
Module to Module	*120*	*4.16*[1]	*2*	*2.5*	*THW*
Array to Control Building					
Array to inverter	*120*	*8.32*	*2*	*4*	*THW*
DC Circuits					
Battery to Battery	*N/A*				
Battery Charger to Battery					
Battery to Inverter or Converter					
Battery to DC load					
Branch Circuit					
1. N/A					
2.					
3.					
4.					
5.					
System Grounding	Wire Size (mm^2)		Wire Type		Type of Earth Ground
Equipment Ground					
System	*6*		*bare copper*		*to ground rod*

Design Notes:

1) Maximum current of a solar module

A simple method for determination of the PV array size of a pumping system is to use the nomogram in Figure 5.8. It relates volume-head product or hydraulic energy, available solar irradiation (this must be defined for the tilted surface and is not for horizontal surface). Moreover, the total pumping subsystem efficiency should include mismatch module and line loss factor. Generally, its value is between 30 and 70 %, depending on the efficiency of the motor/pump which is the main effect on this value. The nomogram that is shown will give the necessary rated size of PV array with a slightly different value from the rated size installed.

In the previous example, the village needs a volume of water of 20 m^3/day and the total pumping head is about 27.54 metres. Thus, the volume-head product is 550.80 m^4/day. Using this value and a subsystem daily energy efficiency of 0.36 with daily solar irradiation of 4.10 kWh/m^2/day (design month) on an inclined surface at latitude angle for Udon Thani province of Thailand, the size of PV array can be found from the nomogram to be approximately 1016 W_P. Alternatively, the equation 5.3 can also give the rated of PV array size with the same result that is found by the nomogram's method. The peak flow rate expressed in litres/second can be found from Figure 5.9 below. It is assumed that at maximum sunlight intensity of 1000 W/m^2, the PV array will produce its maximum rated output. In the example, the value of the peak flow rate will be met which is about 1.4 litres/sec. Practically, water output will vary with the solar irradiation as well.

Another method for calculating the PV array size is to consider the physical system layout, groundwater resource and the solar resource. This method needs more detail than others. Ideally, month by month solar insolation data on tilted surfaces at the design location are required in order to properly assess the suitability of a site for a PV pumping system. In practice, an array tilt angle fixed at the latitude angle will give the best mean annual solar energy collection.

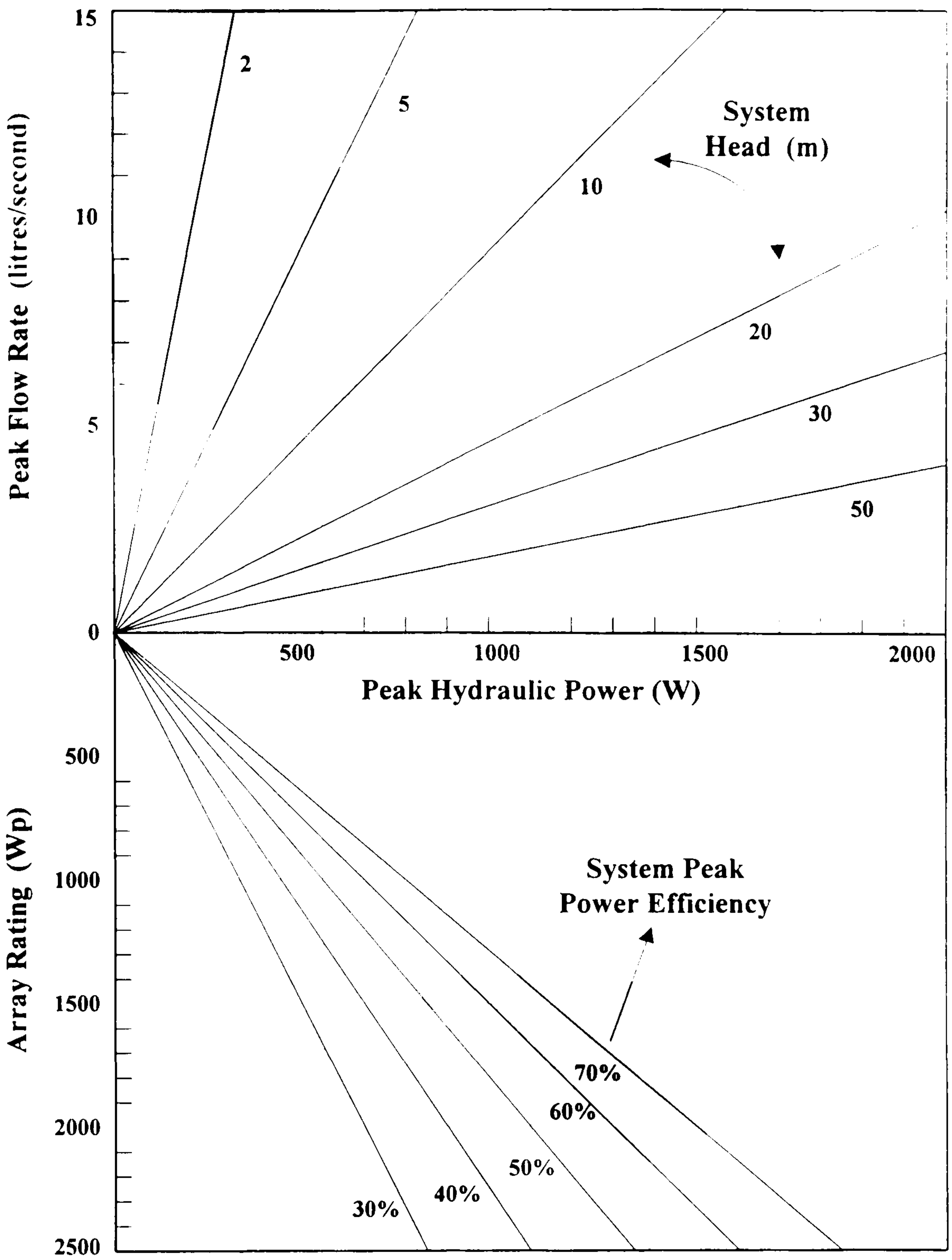


Figure 5.9 Nomogram for determination of peak flow rate of water

However, it is better to tilt the PV array corresponding to the specific angle for receiving the maximum power output in different seasons (see chapter 3). It is an observation that seasonal charges in per capita consumption may be about 15% either side of the mean, with the maximum being in the dry season [8]. If there is no local information on water use, this can be used in the monthly demand calculation and should be varied smoothly between the seasonal extremes. As an example which is shown in Table 5.3, the second column shows the number of people who need water each month and the third column is the ideal total daily demand in m^3/day. As can be seen from Table 5.4, May is the driest month and August is the wettest month for the sample village in Udon Thani of Thailand.

Table 5.3 Calculation of ideal daily requirements for village water supply of the sample village in Udon Thani of Thailand (maximum 500 people estimated).

Month	No. of people	Water required/person (litres)	Total daily demand (m^3)
January	475	37	17.57
February	480	38	18.24
March	500	40	20.00
April	500	40	20.00
May	500	40	20.00
June	475	37	17.57
July	450	34	15.30
August	435	32	13.92
September	440	33	14.52
October	450	34	15.30
November	465	36	16.74
December	470	37	17.39

Since the size of the array depends on the daily solar insolation on the inclined surface and the hydraulic energy requirement, which is called the volume-head product, this must be calculated for each month, and the month that requires the largest array size is called the design month, is the worst case and represents the extreme condition. Therefore if the pump can meet the requirement in this month, then it also can, by definition, meet it for the rest of the months of the year.

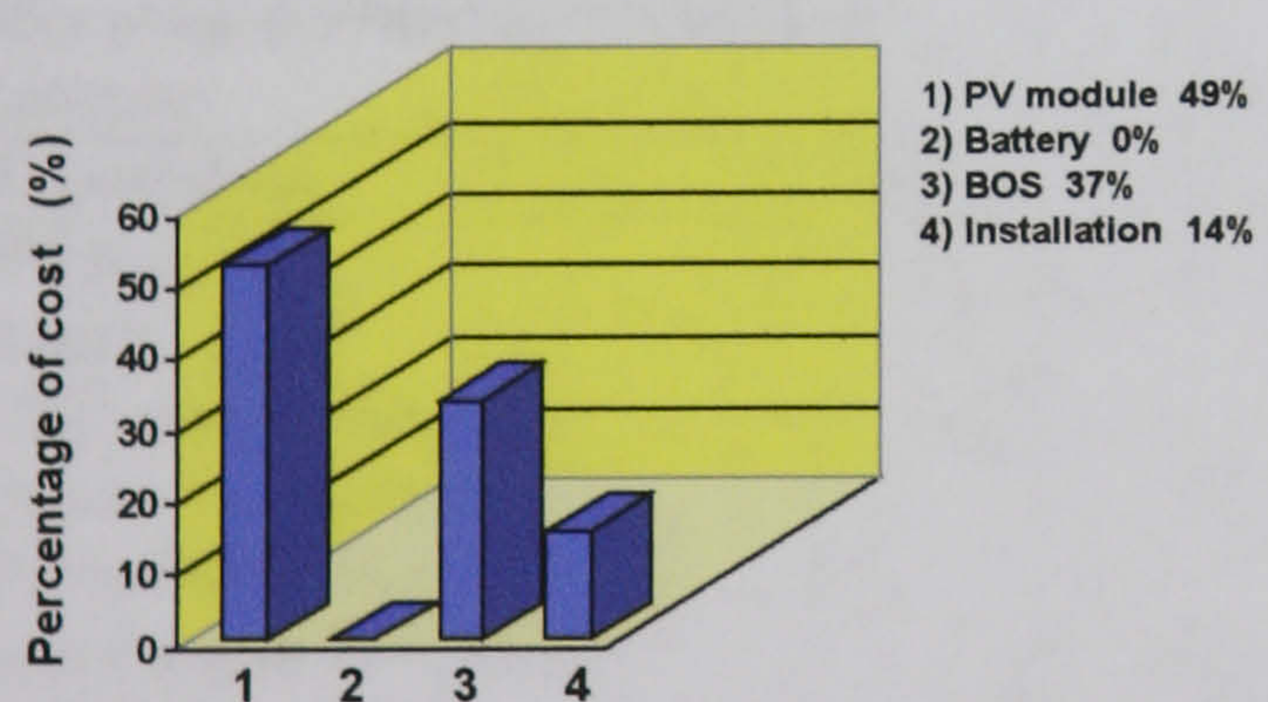
Table 5.4 Array sizing for village water supply in the sample village at Udon Thani.

Month	Total pumping head (m)	Daily water required (m^3/day)	Volume-head product (m^4/day)	Daily solar irradiation (kWh/m^2)	Array rating estimated (W_p)
Jan	25.5	17.57	448.04	5.31	639
Feb	26.0	18.24	474.24	4.73	759
Mar	27.0	20	540.00	4.24	964
Apr	27.1	20	542.00	4.71	871
May	27.5	20	550.00	4.10	1015
Jun	25.5	17.57	448.03	4.40	771
Jul	24.0	15.30	367.2	3.86	720
Aug	23.0	13.92	320.16	3.77	643
Sep	24.1	14.52	350.00	4.41	601
Oct	24.3	15.30	371.80	4.61	611
Nov	24.8	16.74	415.15	4.64	677
Dec	25.0	17.39	434.75	4.89	673

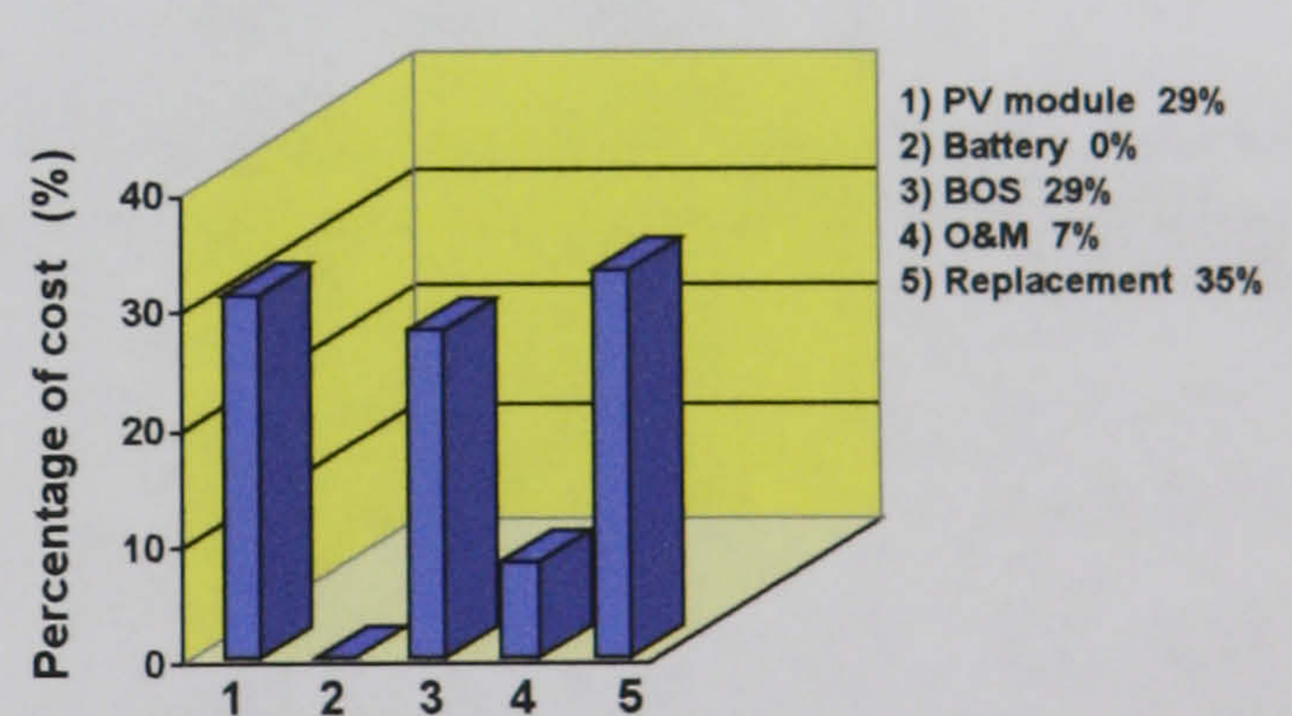
The design month means that the pumping system needs largest PV array size to meet the worst condition and volume of water can be pumped corresponding to water consumption. As can be seen from the table above, May is the design month with the array size of 1015 W_P. However, the estimated size of the PV array is the same result as obtained previously from the design worksheet. In practice, the maximum PV array size installed may be greater than the estimated PV array size depending on the chosen rated power of the solar modules to be used for installation. The critical selection of the suitable PV array size can be discussed as follows:

- If the array size has been sized for the worst month, then in each month at least as much or more than the volume of water required will be pumped. If it can be afforded, the extra water will almost certainly be put to some use, such as storage in a tank.
- If the array size is limited by the well peak flow rate, in some months the actual amount pumped will be less than the specific volume of water required.

5.3.2 Life Cycle Cost Analysis of a PV Pumping System



(a) Capital Cost of a PV Pumping System



(b) Life Cycle Cost of a PV Pumping System

Figure 5.10 Cost elements of a PV pumping system

Table 5.5 Life cycle cost analysis of a PV pumping system

Project/Site : Udon Thani, Thailand		**Type of system :** PV water pumping system		
1. Financial parameters	*Symbol*	*Values*	*Unit*	*Remark*
Period of analysis	n	20	years	project lifetime
Discount rate	d	0.10		
Inflation rate	i	0.05		
Discount factor	a	0.954		$a = (1+i)/(1+d)$
Annualised factor	$P_{a(n)}$	12.65		$P_{a(n)} = a(1-a^n)/(1-a)$
2. System specification and performance				
Load				
Daily load	L_d	4.132	kWh/day	existing data
Annual load	L_a	1508.18	kWh/year	$365*L_d$
Solar Module				
Array size	S_a	1130	W_P	existing data
Module unit price	S_p	6	$\$/W_P$	silicon cells
Lifetime	S_{lt}	20	years	
Battery				
Battery capacity	B_c	-	kWh	
Battery unit price	B_p	-	$/kWh	
Lifetime	B_{lt}	-	years	
Charge Controller				
Charge controller		-	amps	
Charge controller unit price		-	$/amp	
Lifetime		-	years	
Power Conditioner				
Inverter size	I_{in}	1.5	kW	
Inverter unit price	I_p	650	$/kW	
Lifetime	I_{lt}	10	years	
End-user load				
Pumping/motor unit		4000	$	$\$ 4 / W_P$
Lifetime		5	years	
Mounting and Foundation				
Mounting & Foundation unit price	K_p	0.5	$\$/W_P$	
Lifetime	K_{lt}	20	years	
3. Cost data				
PV array	C_{pv}	6780	$	$C_{pv} = S_a * S_p$
Battery		-	$	
Charge controllers		-	$	
Power conditioner	C_{pc}	975	$	$C_{pc} = I_{in} * I_p$
Pump/motor unit		4000	$	
Mounting & Foundation	C_{sw}	565	$	$C_{sw} = S_a * K_p$
Installation (20%)	C_{in}	1356	$	$C_{in} = 0.2*C_{pv}$
a) Capital Cost	C_{cap}	**13676**	$	
Operation & Maintenance (2%)	C_{om}	135.6	$	$C_{om} = 0.02*C_{pv}$
b) Life Cycle O&M Cost	$C_{o\&m}$	**1715.34**	$	$C_{om} * P_{a(n)}$
Replacement Cost	*Yr.(i)*		*PW*	
(i) Battery	5	0.79	-	$PW = C_{bat} * P_{r(i)}$
	10	0.63	-	
	15	0.50	-	
(ii) Power conditioner			614.25	every 10 years
(iii) Pump/motor unit			7680	every 5 years
c) Life Cycle Replacement Cost	C_{rep}		**8294.25**	
d) Salvage	C_{sal}		**-0.0**	
4. Economic indicator				
Total life Cycle Cost	LCC	**23685.60 US$**		LCC = a+b+c-d
Annualised LCC	ALCC	**1872.37 US$/year**		$ALCC = LCC / P_{a(n)}$
Cost of Electricity	COE	**1.24 US$/kWh**		$COE = ALCC / L_a$

5.4 PV Refrigeration Storage System

The use of PV powered refrigerators/freezers (R/F) is increasing for applications requiring high reliability. Medical vaccine refrigerators are the prime example. Extensive immunisation programmes are in progress throughout the developing countries. To be effective, these programmes must provide immunisation services to many rural areas. All vaccines that are used have to kept within a limited temperature range throughout transportation and storage. The provision of refrigeration for this, known as the vaccine "cold chain", is a major logistical undertaking in areas where electricity supplies are non-existent. The most common and suitable principle for electrically operated refrigerators is based on the "vapour compression" cycle. These systems can operate with 220 VAC or 12, 24 VDC power supply. They may be configured with upright cabinets as refrigerators or freezers, or as combination R/F units with single or double compressors [9,10]. The DC refrigerator is more desirable than the AC unit because the efficiency is up to five times higher, which means the power consumption for DC units will be reduced. The mode of operation directly affects the total system cost. Some factors will significantly affect performance, such as the number of users, door operating habits, seasonal variations in use, time and temperature of loading, and the physical location of the unit.

The standard engineering expression of the effectiveness of a vapour compression refrigeration cycle is the "coefficient of performance". This is the ratio of useful heat transfer (refrigeration effect) over the work energy used by the compressor. Well-designed refrigerator can operate between 0.4 and 1.3 kWh/litre/year. Electricity consumption for a refrigeration is between 0.0045-0.01 kWh/day/litre and for a freezer is between 0.006 and 0.036 kWh/day/litre [10,11]. Most conventional AC domestic refrigerators consume between 2 and 5 kWh/litre/year, i.e., 3-8 kWh/day. However, DC units can be much more efficient. For example, APEX has manufactured a model # RSA 215E, 206 litres, 12 or 24 VDC, 60 Watts with an energy consumption of 280 Wh/day at 25°C, or 380 Wh/day at 32°C. In general, the compressor duty cycle of a R/F is between 8 and 10 hours. It is determined by the ambient air condition, the thermostat set points, door operating habits.

In the case of refrigeration options for clinics, vaccine used for immunisation must be transported and stored below critical temperature by means of a reliable "cold chain" to retain their potency. The specific requirements of a medical R/F are, therefore, largely based on immunisation programme needs. The WHO has established minimum specifications for vaccine refrigerators and ice-pack freezers. WHO requires an energy consumption of less than 0.014 kWh/day per 50 litres volume at 43°C and a high holdover time in the event of a compressor failure (approximately 10 hours for a well-insulated unit). Typical energy consumption is 300-500 Wh/day for a 100 litres refrigerator without ice-pack freezing and an ambient temperature of 32°C. At 43°C with 2 Kg ice-pack freezing per day, the energy consumption would be between 600-1200 Wh/day. It is vital that the PV refrigerator is not overloaded. In view of the critical reliability required, vaccine refrigerators are generally supplied as complete, autonomous systems (independent of PV lighting) with their own dedicated array and battery. The recommended battery capacity is for 5 days of complete autonomy. The following criteria are used to access performance

- The rate of ice-pack freezing in kilograms per 24 hours.
- Internal temperature distribution and variation within the permissible range of +0°C to +8°C.
- Holdover time during loss of power. This is the length of time for which the internal temperature for the refrigerator will remain below 8°C when the power supply has been disconnected.

Both refrigerators and freezers are automatically operated in order to keep the deference between the external and internal temperature to a fairly constant value. As a result, the duty cycle is quite constant for a freezer while it changes through the year for a refrigerator and reaches its maximum value during the warmest period of the year. A typical variation of the R/F duty cycle is shown in Figure 5.11.

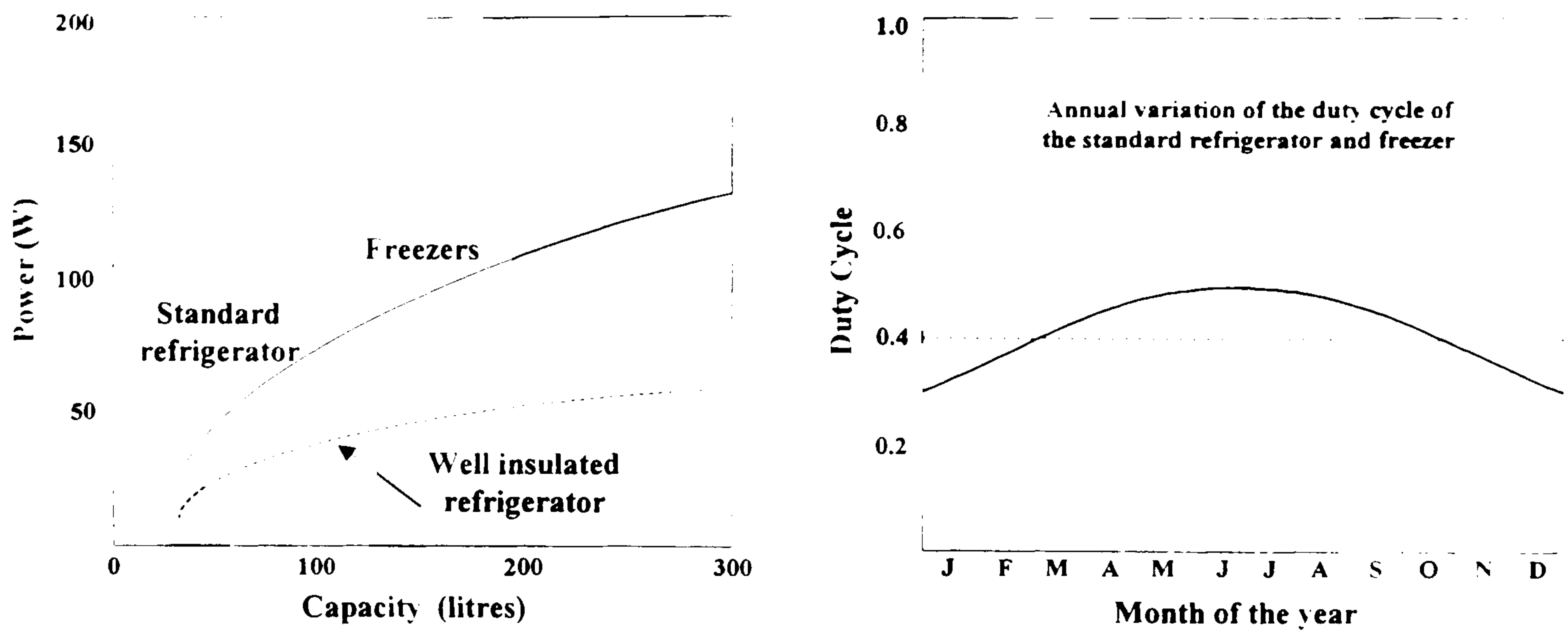


Figure 5.11 Rated power of refrigerator and freezer as a function of their capacity, and a typical graph of duty cycle as a function of the month of the year.

5.4.1 Design of a PV Refrigeration System in the Sample Village

A typical system used in rural areas consists of the main components as follows:

(1) ***PV array*** : It provides electrical power that supplies the load (compressor and batteries).

(2) ***Battery*** : It provides the high availability of PV refrigeration systems.

(3) ***Charge Controller*** : For systems installed in remote areas, the battery charge controller is critical and directly affects life-cycle cost. Select a R/F unit with separate thermostat controls for each compartment. Controllers with meters or warning lights allow the system performance to be monitored easily.

(4) ***Refrigerator*** : Most stand-alone PV refrigerator/freezer systems operate at 12 or 24 VDC. These modern DC units are recommended because of their efficient operation. Most refrigerators include a freezer compartment for ice-pack freezing. Other systems have separate units to provide solely for refrigeration or freezing. Sizes available range is between 10 and 200 litres of vaccine storage capacity, with ice protection rates of up to 5 kg per 24 hours.

GENERAL CONSIDERATIONS

Application :	Refrigerator/Freezer Storage
Site :	Udon Thani, Thailand
Location :	17.3° N, 102.8° E
Environment :	High Plains
Maximum Wind speed :	5.9 m/s (at 600 m height)
Load :	Refrigerator/Freezer

ARRAY :
The array frame should be properly grounded with the ground conductor securely attached to each support structure and the array azimuth should be true south with tilt angle. If vandalism is a possibility, consider elevating the array. All connections should be in water-right junction boxes with strain relief connectors. All wiring should be laced and attached to support structure with nylon wire ties.

CONTROLLER :
For a typical stand-alone PV system installed in remote areas, the battery charge regulation is critical and directly affects life cycle cost, since state of charge of the battery is required to prevent deep discharge and overcharge of the battery, select a refrigeration/freezer unit with separate thermostat controls for each compartment. Manual with mechanical thermostats is recommended over electronic thermostat because of their simplicity and reliability.

BATTERIES :
All batteries will provide the high availability of the PV refrigeration/freezer systems. Deep cycle lead-acid type specifically designed is recommended because it is widely available in many rural shops of Thailand. It is less expensive than nickel-cadmium types. Batteries should be located in a weather resistant enclosure. If non-sealed batteries are used, nonmetallic enclosure is recommended to prevent corrosion. The users should strongly follow a user's battery guideline from the manufacturer.

INVERTER :

Due to the fact that the load is a DC unit, then the system does not need an inverter.

LOAD :
As the initial cost of the high-efficiency DC refrigerator decreases, they can be used in residential applications that have been increasing. In most instances, the DC refrigerator is recommended over the AC refrigerator. Since the efficiency is up to five times higher, as a result, the input power can be significantly reduced. Most stand-alone PV refrigerator or freezer systems operate at 12 V or 24 VDC. These modern types of DC refrigerators/freezers are recommended because of their efficient operation.

WIRING/SWITCH GEAR :
All wiring, fusing should conform to standard electrical procedure. Selecting a suitable size of fuses is critical to protect all system components damages due to short circuit current or over current flows. A fused safety switch should be installed in a rainproof enclosure.

MOUNTING :
PV arrays are either ground mounted or mounted to the building that houses the refrigerator. Although installation the array on the roof of the structure may decrease the possibility of vandalism, precautions should be taken to minimise the possibility of roof leaks and do not use a direct mount. Array frames should be anodized aluminium, galvanized or stainless steel and designed for maximum anticipated wind velocities.

Worksheet #1	Calculation of the daily load demand												
Load description	DC or AC	No. of sets	Load current (A)	Load voltage (V)	DC power (W)	AC power (W)	Daily duty cycle (h/day)	Weekly duty cycle (d/week)	7 days in a week	Power conversion eff. (decimal)	Energy requirement (Wh/day)	Nominal system voltage (V)	Ampere hour load (Ah/day)
			×	×	=	=	×	×	÷	×	=	÷	=
Refrigerator/ Freezer	*DC*	*1*	*3.75*	*24*	*90*	*N/A*	*10*	*7*	*7*	*1*	*900*	*24*	*37.5*
				Total DC load power (W)	*90*	*N/A*	Total AC load power (W)			Total Wh/day	*900*	Total Ah/day	*37.5*

Design Notes

Maximum Tilt Angle Worksheet # 2	**Estimate The Maximum Tilt Angle (for Refrigeration System)**

Site : *Udon Thani of Thailand* **Latitude :** *17.38°N* **Longitude :** *102.72°E*

Tilt at latitude - 25°

Month	Ampere-hours load (Ah/day)		Peak sun (h/day)		Current (A)	Select the largest current and corresponding peak sun	
Jan.	*37.5*	÷	*5.773*	=	*6.49*		
Feb.	*37.5*	÷	*4.780*	=	*7.84*		
Mar.	*37.5*	÷	*3.969*	=	*9.45*		
Apr.	*37.5*	÷	*4.105*	=	*9.13*		
May	*37.5*	÷	*3.392*	=	*11.05*	latitude - 25°	
Jun.	*37.5*	÷	*3.508*	=	*10.68*	peak sun	current
Jul.	*37.5*	÷	*3.166*	=	*11.84*	(h/day)	(A)
Aug.	*37.5*	÷	*3.233*	=	*11.60*	*3.166*	*11.84*
Sep.	*37.5*	÷	*4.003*	=	*9.36*		
Oct.	*37.5*	÷	*4.543*	=	*8.25*		
Nov.	*37.5*	÷	*4.898*	=	*7.65*		
Dec.	*37.5*	÷	*5.400*	=	*6.94*		

Tilt at latitude

Month	Ampere-hours load (Ah/day)		Peak sun (h/day)		Current (A)		
Jan.	*37.5*	÷	*5.317*	=	*7.05*		
Feb.	*37.5*	÷	*4.737*	=	*7.91*		
Mar.	*37.5*	÷	*4.246*	=	*8.83*		
Apr.	*37.5*	÷	*4.714*	=	*7.95*		
May	*37.5*	÷	*4.105*	=	*9.13*	latitude	
Jun.	*37.5*	÷	*4.407*	=	*8.51*	peak sun	current
Jul.	*37.5*	÷	*3.859*	=	*9.71*	(h/day)	(A)
Aug.	*37.5*	÷	*3.773*	=	*9.94*	*3.773*	*9.94*
Sep.	*37.5*	÷	*4.409*	=	*8.50*		
Oct.	*37.5*	÷	*4.617*	=	*8.12*		
Nov.	*37.5*	÷	*4.642*	=	*8.08*		
Dec.	*37.5*	÷	*4.918*	=	*7.625*		

Tilt at latitude + 25°

Month	Ampere-hours load (Ah/day)		Peak sun (h/day)		Current (A)		
Jan.	*37.5*	÷	*4.104*	=	*9.13*		
Feb.	*37.5*	÷	*4.065*	=	*9.22*		
Mar.	*37.5*	÷	*4.001*	=	*9.37*		
Apr.	*37.5*	÷	*4.805*	=	*7.80*		
May	*37.5*	÷	*4.385*	=	*8.55*	latitude + 25°	
Jun.	*37.5*	÷	*4.856*	=	*7.72*	peak sun	current
Jul.	*37.5*	÷	*4.164*	=	*9.00*	(h/day)	(A)
Aug.	*37.5*	÷	*3.904*	=	*9.60*	*3.744*	*10.01*
Sep.	*37.5*	÷	*4.272*	=	*8.77*		
Oct.	*37.5*	÷	*4.089*	=	*9.17*		
Nov.	*37.5*	÷	*3.755*	=	*9.98*		
Dec.	*37.5*	÷	*3.744*	=	*10.01*		

Now select the latitude angle that give the smallest current and corresponding peak sun from each latitude and enter on the right hand side	peak sun (h/day)	current (A)
	3.773	*9.94*
	Max. tilt angle selected	
Note : This angle is for fixed tilt angle throughout the year	*17°*	

Design Notes :

Refrigeration System Worksheet # RS	Calculation of PV Array and Battery Sizing

Site : *Udon Thani, Thailand*	Battery efficiency : *85 %*
Daily load : *900* Wh/day	Max. DOD : *70 %*
Tilt angle : *17* degrees	Regulator efficiency : *85 %*
Monthly mean daily solar radiation: *3.773* kWh/m^2	Line loss factor : *5 %*
Availability required : *Critical Design*	Nominal system voltage : *24* VDC

1) PV Array Sizing

Ampere-hour load (Ah/day)		Regulator efficiency (decimal)		Battery efficiency (decimal)		Line loss factor (decimal)		Corrected amperes- hour (Ah/day)
37.5	÷	*0.85*	÷	*0.85*	÷	*0.95*	=	*54.63*

Corrected ampere-hours (Ah/day)		Peak sun hours at selected tilt angle (h/day)		Module degradation factor (decimal)		Corrected array current (A)
54.63	÷	*3.773*	÷	*0.9*	=	*16.09*
				Rated current of a PV module	÷	*4.72*
				Number of modules connected in parallel	=	*(3.4) ~ 4*

Nominal system voltage (V)		Nominal voltage of a PV module (V)		No. of modules connected in series		No. of modules connected in parallel		Total number of modules used
24	÷	*12*	=	*2*	×	*4*	=	*8*

2) Battery Sizing

Corrected ampere-hour (Ah/day)		Days of autonomy (day)		Max. depth of discharge (decimal)		Corrected battery capacity (Ah)		Each battery capacity (Ah)		No. of batteries connected in parallel
54.63	×	*5*	÷	*0.7*	=	*390.2*	÷	*130*	=	*3*

Nominal system voltage (V)		Nominal battery voltage (V)		No. of batteries connected in series		No. of batteries connected in parallel		Total number of batteries used
24	÷	*12*	=	*2*	×	*3*	=	*6*

PV module information		**Battery information**
Manufacturer : *BP Solar*		Manufacturer : *Trojan*
Model : *BP585F*		Model : *SCS-225*
Type : *monocrystalline silicon (36 series cells)*		Type : *Lead-Acid, Deep Cycle*
SC current : *5* A	OC voltage : 22.3 V	Nominal voltage : *12* V
Max. current : *4.72* A_{mp}	Max. voltage : 18 V_{mp}	Capacity : *130* Ah

Design Notes :

1) *Days of autonomy is specified by WHO.*

Charge Controller General Worksheet # CC				Technical Specifications of Charge Controller							
Short circuit current of a module (A)		No. of modules connected in parallel		Safety factor		Design controller capacity (A)		Each rated ampere of controller (A)		No. of controllers in parallel	
5	×	*4*	×	**1.25**	=	*25*	÷	*30*	=	*(0.83) ~ 1*	

Manufacturer : *BP Solar* Regulator Type : *GCR-3000 (m)* System voltage (V) *: 24* Maximum load current (A) : *30 (at 50 ℃)* Operating temperature (°C) : *-25 °C to +50 °C* Disconnection pre-warning : *SOC<40% (23.4 V)* Disconnection level : *SOC < 30% (22.2 V)* Reconnection level : *: SOC > 50% (25.2 V)* ***Metering and protection*** Voltage : ✓❑ Yes ❑ No Current : ✓❑ Yes ❑ No State of Charge (SOC) : ✓❑ Yes ❑ No Under and Overvoltage : ✓❑ Yes ❑ No Over-temperature, load current : ✓❑ Yes ❑ No Others : LED display for charge control and over-discharge protection	**<u>Design Notes :</u>** *Regulator must be provided with suitable mounting brackets or/and fixing*

Protection of System Components General Worksheet # PSC	Protection of System Components

Array Description								
Array short circuit current (A)		No. of modules connected in parallel		Total array short circuit current (A)		Safety factor		Rated current of protective device (A)
5	×	*4*	=	*20*	×	**1.25**	=	*25*
Controller/ Main Load Description								
Total DC load power (W)		Nominal system voltage (V)		Maximum DC load current (A)		Safety factor		Rated current of protective device (A)
90	÷	*24*	=	*3.75*	×	**1.25**	=	*4.68*
Battery Description								
Maximum current of a module (A)		No. of modules connected in parallel		Peak current from PV array (A)		Safety factor		Rated current of protective device (A)
4.72	×	*4*	=	*18.88*	×	**1.25**	=	*23.6*
Inverter Description								
Total AC load power (W)		Nominal system voltage (V)		Power factor (decimal)		Safety factor		Rated current of protective device (A)
	÷		÷		×	**1.25**	=	*N/A*

Branch Circuit # 1 (Refrigerator/Freezer)					Branch Circuit # 2 (Specify)				
Rated load current (A)		Safety factor		Rated current of protective device (A)	Rated load current (A)		Safety factor		Rated current of protective device (A)
3.75	×	**1.25**	=	*4.68*[1]		×	**1.25**	=	*N/A*
Branch Circuit # 3 (Specify)					**Branch Circuit # 4 (Specify)**				
Rated load current (A)		Safety factor		Rated current of protective device (A)	Rated load current (A)		Safety factor		Rated current of protective device (A)
	×	**1.25**	=	*N/A*		×	**1.25**	=	*N/A*

Circuit	Protective Device (No. of Devices)				Rated Current	Rated Voltage	Descriptions
	CB	Fuse	Switch	Surge	(A)	(V)	
Array to controller		*2*			*25*	*250*	*HBC fuse*[2]
Controller to battery			*1*		*25*	*250*	*DPST switch*[3]
Controller to DC load		*1*			*6*	*250*	*HBC fuse*

Design Notes:

1) Rated current is the same as rated current of main load because this system has only R.F load.
2) High Breaking Capacity fuse with fuse-holder 30 A rated.
3) Double Pole Single Throw switch.

DC Wring General Worksheet # DCW		DC Wire Sizing Specification			
Descriptions	System voltage (V)	Maximum current (A)	Allowable voltage drop (%)	Wire size (mm^2)	Wire type
Array Circuit					
Module to Module	*24*	*4.72*	*2*	*2.5^1*	*THW*
Array to Control Building					
Array to Controller	*24*	*25*	*2*	*4*	*THW*
DC Circuits					
Battery to Battery					
Regulator to Battery	*24*	*23.6*	*2*	*4*	*THHN (battery cable)*
Battery to Inverter or Converter					
Controller to DC load	*24*	*4.68*	*3*	*2.5*	*THW*
Branch Circuit					
1. *refrigerator/freezer*	*24*	*4.68*	*3*	*2.5*	*THW*
2. *N/A*					
3.					
4.					
5.					
System Grounding	Wire Size (mm^2)		Wire Type		Type of Earth Ground
Equipment Ground	*6*		*bare copper*		*to ground rod*
System	-		-		-

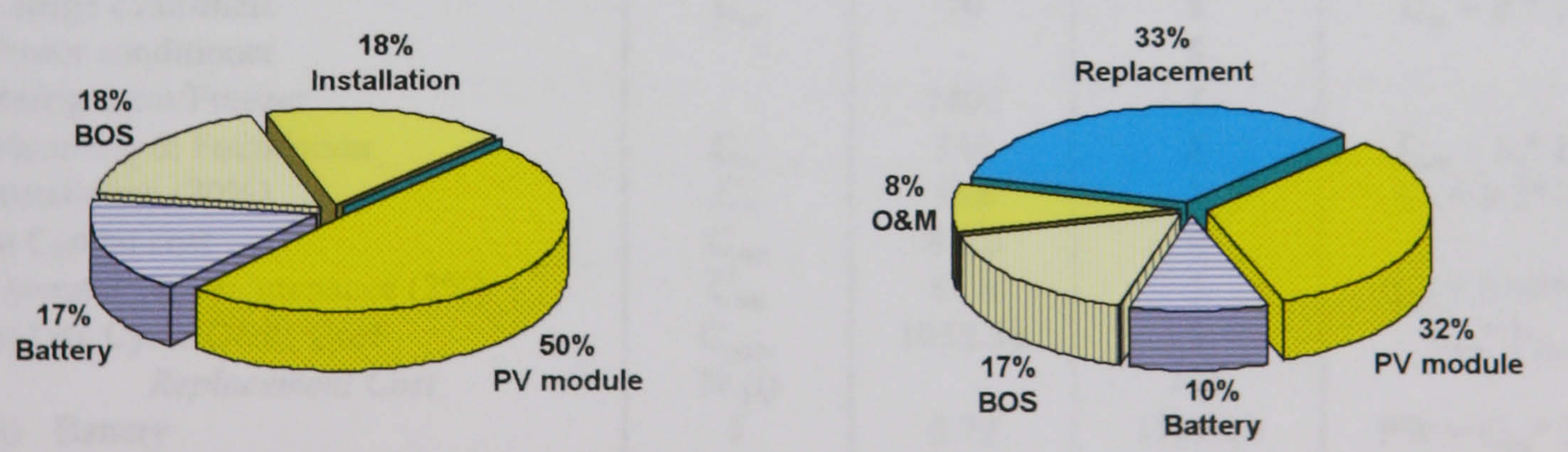
Design Notes:

1) The minimum size of cable must be ≥ 2.5 mm^2 for general installation.

2) For charge regulator to battery must be ≥ 4 mm^2.

3) For grounding system must be ≥ 6 mm^2.

5.4.2 Life Cycle Cost Analysis of a PV Refrigeration System



(a) Capital Cost of a Refrigeration Storage System

(b) Life Cycle Cost of a Refrigeration Storage System

Figure 5.12 Cost elements of a refrigeration storage system

Table 5.6 Life cycle cost analysis of a PV refrigeration system

Project/Site : Udon Thani, Thailand		**Type of system :** PV refrigeration storage		
1. Financial parameters	*Symbol*	*Values*	*Unit*	*Remark*
Period of analysis	n	20	years	project lifetime
Discount rate	d	0.10		
Inflation rate	i	0.05		
Discount factor	a	0.954		$a = (1+i)/(1+d)$
Annualised factor	$P_{a(n)}$	12.65		$P_{a(n)} = a(1-a^n)/(1-a)$
2. System specification and performance				
Load				
Daily load	L_d	0.9	kWh/day	
Annual load	L_a	328.5	kWh/year	$365*L_d$
Solar Module				
Array size	S_a	680	W_p	existing data
Module unit price	S_p	6	$/$W_p$	silicon cells
Lifetime	S_{lt}	20	years	
Battery				
Battery capacity	B_c	9.36	kWh	existing data
Battery unit price	B_p	150	$/kWh	
Lifetime	B_{lt}	5	years	
Controller				
Charge controller	R_t	10	amp	
Charge controller unit price	R_p	7	$/amp	
Controller lifetime	R_{lt}	5	years	
Power Conditioner				
Inverter size	I_{in}	-	kW	
Inverter unit price	I_p	-	$/kW	
Lifetime	I_{lt}	-	years	
End-user loads				
Refrigerator/Freezer		1400	$	
Lifetime		10	years	
Mounting and Foundation				
Mounting & Foundation unit price	K_p	0.5	$/$W_p$	
Lifetime	K_{lt}	20	years	
3. Cost data				
PV array	C_{pv}	4080	$	$C_{pv} = S_a * S_p$
Battery	C_{bat}	1404	$	$C_{bat} = B_c * B_p$
Charge controllers	C_{cc}	70	$	$C_{cc} = R_t * R_p$
Power conditioner		-	$	
Refrigerator/Freezer		1400	$	
Mounting & Foundation	C_{sw}	340	$	$C_{sw} = S_a * K_p$
Installation (20%)	C_{in}	816	$	$C_{in} = 0.2*C_{pv}$
a) Capital cost	C_{cap}	**8110**	$	
Operation & Maintenance (2%)	C_{om}	81.6	$	$C_{om} = 0.02*C_{pv}$
b) Life Cycle O&M Cost	$C_{o\&m}$	**1032.24**	$	$C_{om} * P_{a(n)}$
Replacement Cost	*Yr.(i)*		*PW*	
(i) Battery	5	0.79	1109.16	$PW = C_{bat} * P_{r(i)}$
	10	0.63	884.52	
	15	0.50	702	
(ii) Charge controllers			1344	every 5 years
(iii) Refrigerator/Freezer			882	every 10 years
c) Life Cycle Replacement Cost	C_{rep}		**4921.68**	
d) Salvage	C_{sal}		**-0.0**	
4. Economic indicator				
Total Life Cycle Cost	LCC	**14063.92 US$**		$LCC = a+b+c-d$
Annualised LCC	ALCC	**1111.77 US$/year**		$ALCC = LCC/P_{a(n)}$
Cost of Electricity	COE	**3.38 US$/kWh**		$COE = ALCC/L_a$

5.5 PV Public Lighting Systems in Rural Areas

The electric lamps that are working on solar energy in a rural area can represent a non-polluting alternative source compared to the conventional lighting. They are highly economical in places without an electrical network as neither cabling nor main's connection is necessary. An autonomous lighting system is to provide lighting in isolated sites. According to a typical rural environment, stand-alone PV public lighting systems can be mainly applied as lighting for dangerous points or intersections, pedestrian crossings, ferry stations, access to the villages or the towns, public places, bus stops (school buses), camping sites, areas for activities and so on.

In the design of a PV public lighting system the following items should be considered:

(1) *Lamps for Public Lighting System*

Most lamps used in PV public lighting systems are low pressure sodium lamps. Although the colour of the light emitted from the lamps is golden-white, they operate at a wavelength close to the peak sensitivity of the human eye and provide the highest luminous efficiency compared with other lamps. The wattage of lamps that are widely used is 18, 26 and 35 W for street lamps. They provide luminosity of 1800, 3320 and 4800 lumens respectively [12,13]. Generally, a street lamp with 26 W (low pressure sodium) is recommended because it provides a somewhat higher efficiency (lumens/W) than a lamp with 18 W. Furthermore, the lamps should be strong but lightweight and the housing must be sealed to IP65 by a high quality Neoprene gasket. The lens should be vandal resistant and hinge down from stainless steel hinges for easy maintenance. Some manufacturers will provide a high efficiency inverter within the housing designed specially to operate 18 W or 26 W low pressure sodium lamps from a 12 VDC supply.

(2) *Battery and Box*

A water proof battery box is commonly inserted in the concrete basement, and closed with special anti-theft screws. This makes it difficult to access for maintenance of the battery with regular addition of water. Maintenance-free batteries with valve-regulated sealed are strongly recommended. This is because they will never require water. Even though lead-acid batteries are commonly used for PV public lighting systems, nickel-cadmium batteries are also used in some special circumstances. The nickel-cadmium batteries are more expensive than lead-acid type. These batteries are designed for deep cycle and low self discharge as needed for this PV application.

(3) *Control Unit*

This is one of the most important parts of the system. The main features of this part of the system are voltage regulation to protect battery against over charging and deep discharges, and the possibility of programming the length and periods of the operation of the lamp. In addition, a special function can be operated to recognise the different length of day and night throughout the year and adapts itself to the seasons automatically. A conventional solar-driven street lamp tends to fail at least for some nights in winter. This is because it consumes a fixed quantity of energy every day until the battery is completely discharged. From that moment on, the lamp can spend in the night only the amount of energy it gained during the day. In long periods with bad weather this can lead to total breakdown for at least some nights. As a result, some manufacturers have designed a special function called an "intelligent management system", based on a micro processor, which constantly compares the irradiation and the charging condition of the battery to calculate the optimum control sequences [14,15]. Reducing the lighting times in the periods with bad weather prevents a total breakdown. Furthermore the management system will save energy in times when no light is required.

5.4.1 Design of a PV Public Lighting System in the Sample Village

GENERAL CONSIDERATIONS

Application :	Public lighting
Site :	Udon Thani, Thailand
Location :	17.3° N, 102.8° E
Environment :	High Plains
Maximum Wind speed :	5.9 m/s (at 600 m height)
Load :	Low pressure sodium lamps

ARRAY :
PV modules can be fixed mounted on a mast in one piece with an optimum tilt angle or 90° depending on model of manufacturers, some models are made of high grade steel in a very sophisticated design. However, mounting with an optimum tilt angle is recommended. PV module should be high (between 3.50 m and 5.50 m), the array azimuth should be true south. All connections should be in water-tight junction boxes with strain relief connectors.

CONTROLLER : To use a control device in PV public lighting is very important. Some devices can enable the achievement of such comfort and reliability that it is comparable to conventional, network-driven systems. It adapts the energy consumption to the available energy by determining the lighting period of the PV lamp according to the energy input and charging condition of the battery. Possibility of programming the length and periods of operation of the lamp. Protection of the battery from damage from deep discharge and overcharge by a controller must be considered in this stage.

BATTERIES :
The battery and a control device should be situated inside the water proof battery box that is inserted in the concrete basement. The battery case should be closed with special anti-theft screws. The maintenance free, valve-regulated sealed batteries are strongly recommended. Batteries which have a low self-discharge are also recommended. Lead-acid and lead-gel battery types are used in this PV application. Battery must be protected against overload and deep discharges as well.

INVERTER :

Due to the fact that the load is a DC unit, then the system does not need an inverter.

LOAD :
Although low pressure sodium lamps emit the colour as the golden light, they provide higher efficiency in lumen per wattage compared with the common lamp used in a PV lighting system. In the case of public lighting, low pressure sodium lamps are recommended. Linear fluorescent lamp can be used but its lifetime is shorter than the low pressure sodium lamp and the efficiency is lower. The lamp housing should be sealed to IP65 by a high quality neoprene gasket and protected from vandalism.

WIRING/SWITCH GEAR :
All wiring for the PV public lighting system should be concealed in a mast and all holes punched must be tightly sealed with the gaskets to prevent rain water getting into the inside of a mast. Fuses can be located in the case of the control unit.

MOUNTING :
PV modules on a mast should be mounted in an area clear from shading. Strong wind over 10 m/s in some areas can topple a mast. It is suggested that the maximum speed of local wind should be known before making a decision to install. All mounting structures should be constructed from stainless steel or aluminium to protect from corrosion, but plastic fittings are options.

Worksheet #1	Calculation of the daily load demand												
Load description	DC or AC	No. of sets	Load current (A)	Load voltage (V)	DC power (W)	AC power (W)	Daily duty cycle (h/day)	Weekly duty cycle (d/week)	7 days in a week	Power conversion eff. (decimal)	Energy requirement (Wh/day)	Nominal system voltage (V)	Ampere hour load (Ah/day)
			×	×	=	=	×	×	÷	÷	=	÷	=
Low pressure sodium SOX 26	*DC*	*1*	*2.49*	*12*	*29.88*	-	*6*	*7*	*7*	*1.0*	*179.28*	*12*	*14.94*
Total DC load power (W)					***29.88***	***N/A***	**Total AC load power (W)**			**Total Wh/day**	***179.28***	**Total Ah/day**	***14.94***

Design Notes:

1) *Load current is measured while the* ***high*** *efficiency inverter is connected to operate the lamp.*
2) *Low pressure sodium lamp* ***in*** *this table is based on one set.*
3) *The total number of sets (posts)* ***in*** *the village is 20.*
4) *The wattage size of lamp is widely available in many rural shops* ***of Thailand***.

Maximum Tilt Angle Worksheet # 2	Estimate The Maximum Tilt Angle (for Public Lighting System)

Site : *Udon Thani of Thailand* **Latitude :** *17.38°N* **Longitude :** *102.72°E*

Tilt at latitude - 25°

Month	Ampere-hours load (Ah/day)		Peak sun (h/day)		Current (A)	Select the largest current and corresponding peak sun	
Jan.	14.94	÷	5.773	=	2.58		
Feb.	14.94	÷	4.780	=	3.12		
Mar.	14.94	÷	3.969	=	3.76		
Apr.	14.94	÷	4.105	=	3.64		
May	14.94	÷	3.392	=	4.40	latitude - 25°	
Jun.	14.94	÷	3.508	=	4.25	peak sun (h/day)	current (A)
Jul.	14.94	÷	3.166	=	4.72		
Aug.	14.94	÷	3.233	=	4.62	3.166	4.72
Sep.	14.94	÷	4.003	=	3.73		
Oct.	14.94	÷	4.543	=	3.28		
Nov.	14.94	÷	4.898	=	3.05		
Dec.	14.94	÷	5.400	=	2.76		

Tilt at latitude

Month	Ampere-hours load (Ah/day)		Peak sun (h/day)		Current (A)		
Jan.	14.94	÷	5.317	=	2.81		
Feb.	14.94	÷	4.737	=	3.15		
Mar.	14.94	÷	4.246	=	3.51		
Apr.	14.94	÷	4.714	=	3.17		
May	14.94	÷	4.105	=	3.64	latitude	
Jun.	14.94	÷	4.407	=	3.39	peak sun (h/day)	current (A)
Jul.	14.94	÷	3.859	=	3.87		
Aug.	14.94	÷	3.773	=	3.96	3.773	3.96
Sep.	14.94	÷	4.409	=	3.38		
Oct.	14.94	÷	4.617	=	3.23		
Nov.	14.94	÷	4.642	=	3.22		
Dec.	14.94	÷	4.918	=	3.03		

Tilt at latitude + 25°

Month	Ampere-hours load (Ah/day)		Peak sun (h/day)		Current (A)		
Jan.	14.94	÷	4.104	=	3.64		
Feb.	14.94	÷	4.065	=	3.67		
Mar.	14.94	÷	4.001	=	3.73		
Apr.	14.94	÷	4.805	=	3.11		
May	14.94	÷	4.385	=	3.40	latitude + 25°	
Jun.	14.94	÷	4.856	=	3.07	peak sun (h/day)	current (A)
Jul.	14.94	÷	4.164	=	3.58		
Aug.	14.94	÷	3.904	=	3.82	3.744	3.99
Sep.	14.94	÷	4.272	=	3.49		
Oct.	14.94	÷	4.089	=	3.65		
Nov.	14.94	÷	3.755	=	3.97		
Dec.	14.94	÷	3.744	=	3.99		

	peak sun (h/day)	current (A)
Now select the latitude angle that give the smallest current and corresponding peak sun from each latitude and enter on the right hand side	3.773	3.96
	Max. tilt angle selected	
Note : This angle is for fixed tilt angle throughout the year	17°	

Design Notes :

Public Lighting System Worksheet # PLS	Calculation of PV Array and Battery Sizing
Site : *Udon Thani, Thailand*	Battery efficiency : *85 %*
Daily load : *14.94* Ah/day	Max. DOD : *70 %*
Tilt angle : *17* degrees	Regulator efficiency : *85 %*
Monthly mean daily solar radiation : *3.773* kWh/m^2	Line loss factor : *5 %*
Availability required : *Critical Design*	Nominal system voltage : *12* VDC

1) PV Array Sizing

Ampere-hours load (Ah/day)		Regulator efficiency (decimal)		Battery efficiency (decimal)		Line loss factor (decimal)		Corrected ampere-hours (Ah/day)
14.94	÷	*0.85*	÷	*0.85*	÷	*0.95*	=	*21.76*

Corrected ampere-hours (Ah/day)		Peak sun hours at selected tilt angle (h/day)		Module degradation factor (decimal)		Corrected array current (A)
21.76	÷	*3.773*	÷	*0.9*	=	*6.408*
				Rated current of a PV module	÷	*4.16*
				Number of modules connected in parallel	=	*(1.54) ~ 2*

Nominal system voltage (V)		Nominal voltage of a PV module (V)		No. of modules connected in series		No. of modules connected in parallel		Total number of modules used
12	÷	*12*	=	*1*	×	*2*	=	*2*

2) Battery Sizing

Corrected ampere-hours (Ah/day)		Days of autonomy (day)		Max. depth of discharge (decimal)		Corrected battery capacity (Ah)		Each battery capacity (Ah)		No. of batteries connected in parallel
21.76	×	*5*	÷	*0.7*	=	*155.42*	÷	*100*	=	*(1.55) ~ 2*

Nominal system voltage (V)		Nominal battery voltage (V)		No. of batteries connected in series		No. of batteries connected in parallel		Total number of batteries used
12	÷	*12*	=	*1*	×	*2*	=	*2*

PV module information		Battery information
Manufacturer : *BP Solar*		Manufacturer : *BP Solar*
Model : *BP270*		Model : *PVX 1285*
Type : *monocrystalline silicon (36 series cells)*		Type : *Lead-Calcium, Maintenance-Free*
SC current : *4.48* A	OC voltage : *21.4* V	Nominal voltage : *12* V
Max. current : *4.16* A_{MP}	Max. voltage : *17* V_{MP}	Capacity : *100* Ah (C_{100})

Design Notes :

1) Number of modules connected in parallel is rounded up to 2 modules because of its critical design.
2) Solar module should be fixed with special anti theft screws.
3) A water proof battery should be inserted in the concrete basement. The battery case must be closed with special anti theft screws.

Charge Controller General Worksheet # CC	Technical Specifications of Charge Controller

Short circuit current of a module (A)		No. of modules in parallel		Safety factor		Design controller capacity (A)		Each rated ampere of controller (A)		No. of controllers in parallel
4.48	×	*2*	×	**1.25**	=	*11.2*	÷	*12*	=	*1*

Manufacturer : *Engcotec*
Regulator Type : *IMS*
System voltage (V) : *12*
Maximum load current (A) : *12*
Operating temperature (˚C) : *N/A*
Fuse rating (A) : *N/A*
Disconnection pre-warning : *N/A*
Disconnection level : *N/A*
Reconnection level : *N/A*

Metering and protection

Voltage : ❑ Yes ✓❑ No
Current : ❑ Yes ✓❑ No
State of Charge (SOC) : ✓❑ Yes ❑ No
Under and Overvoltage : ✓❑ Yes ❑ No
Over-temperature, load current : ❑ Yes ✓❑ No
Others : LED display for charge control and over-discharge protection

Design Notes :

Charge controller in street light means a control unit used as the intelligent management device including protection against over charging and deep discharging of a battery and programming of street lamp's operation per night

Protection of System Components General Worksheet # PSC	Protection of System Components

Array Description								
Short circuit current of a module (A)	No. of modules connected in parallel		Total array short circuit current (A)		Safety factor		Rated current of protective device (A)	
4.48	×	*2*	=	*8.96*	×	**1.25**	=	*11.2*
Controller / Main Load Description								
Total DC load power (W)	Nominal system voltage (V)		Maximum DC load current (A)		Safety factor		Rated current of protective device (A)	
29.88	÷	*12*	=	2.50	×	**1.25**	=	*3.12*
Battery Description								
Maximum current of a module	No. of modules connected in parallel		Peak current from PV array (A)		Safety factor		Rated current of protective device (A)	
4.16	×	*2*	=	*8.32*	×	**1.25**	=	*10.4*
Inverter Description								
Total AC load power (W)	Nominal system voltage (V)		Power factor (decimal)		Safety factor		Rated current of protective device (A)	
-	÷	-	÷	-	×	**1.25**	=	*N/A*

Branch Circuit # 1 (specify)					Branch Circuit # 2 (specify)				
Rated load current (A)	Safety factor		Rated current of protective device (A)		Rated load current (A)	Safety factor		Rated current of protective device (A)	
	×		=	*N/A*		×		=	*N/A*
Branch Circuit # 3 (specify)					**Branch Circuit # 4 (specify)**				
Rated load current (A)	Safety factor		Rated current of protective device (A)		Rated load current (A)	Safety factor		Rated current of protective device (A)	
	×		=	*N/A*		×		=	*N/A*

Circuit	Protective Device (No. of Devices)				Rated Current	Rated Voltage	Descriptions
	CB	Fuse	Switch	Surge	(A)	(V)	
Array to controller		*1*			*15*	*250*	*HBC fuse*
Controller to battery		*1*			*15*	*250*	"
Controller to lamp		*1*			*4*	*250*	"

Design Notes:

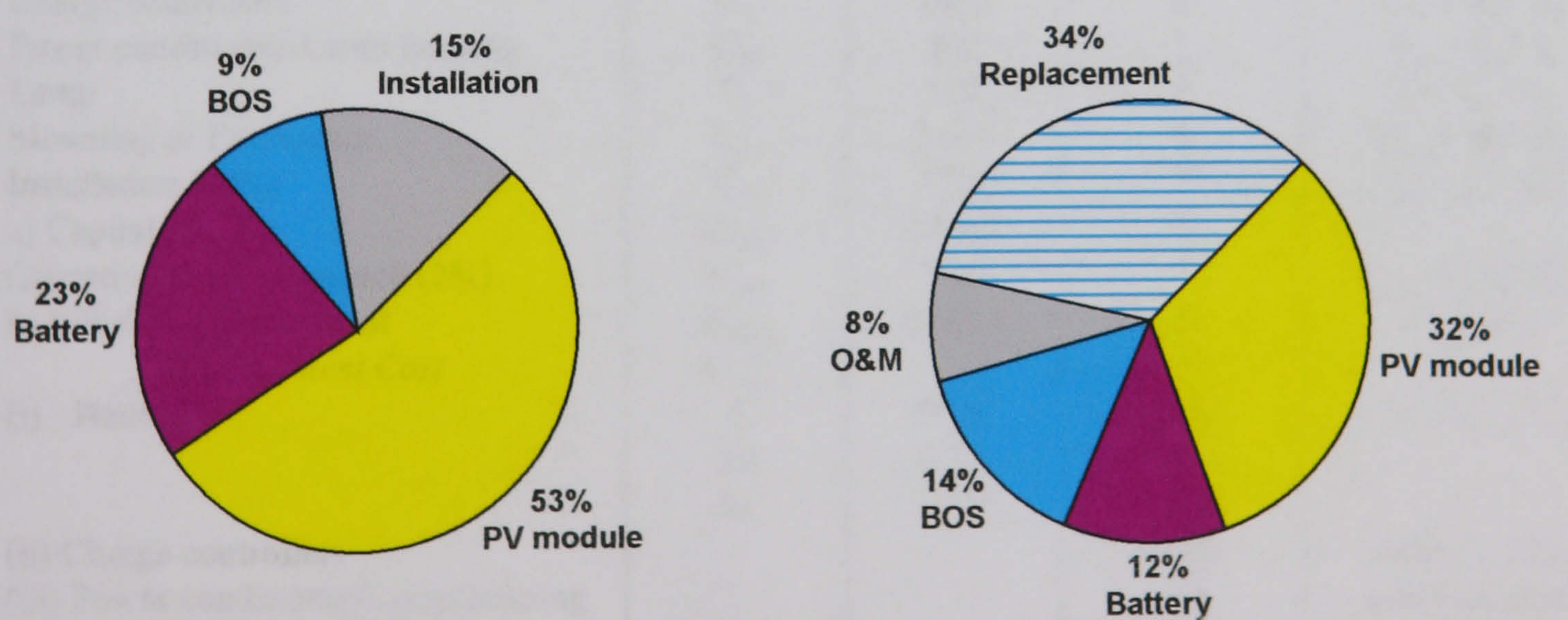
1) *High Breaking Capacity fuse with fuse-holder 30 A rated and connected in series on positive line.*

DC Wring General Worksheet # DCW	DC Wire Sizing Specification				
Descriptions	System voltage (V)	Maximum current (A)	Allowable voltage drop (%)	Wire size (mm^2)	Wire type
Array Circuit					
Module to Module					
Array to Control Building					
Array to Controller	*12*	*11.2*	*2*	*2.5*	*THW*
DC Circuits					
Battery to Battery					
Battery Charger to Battery					
Regulator to battery	*12*	*10.4*	*2*	*6*	*THHN (battery cable)*
Regulator to lamp	*12*	*3.12*	*3*	*2.5*	*THW*
Branch Circuit					
1.					
2.					
3.					
4.					
5.					
System Grounding	Wire Size (mm^2)		Wire Type		Type of Earth Ground
Equipment Ground	-		-		-
System	*6*		*bare copper*		*to ground rod*

Design Notes:

1) *The minimum conductor size of battery must be $\geq 6\ mm^2$ for battery wiring.*
2) *This sheet is only based on one set .*
3) *The total number of sets in the village is 20.*

5.5.2 Life Cycle Cost Analysis of a PV Public Lighting System



(a) Capital Cost of Public Lighting Systmes **(B) Life Cycle Cost of Public Lighting Systmes**

Figure 5.13 Cost elements of public lighting systems

Table 5.7 Life cycle cost analysis of a PV public lighting system

Project/Site : Udon Thani, Thailand		**Type of system :** PV public lighting		
1. Financial parameters	*Symbol*	*Values*	*Unit*	*Remark*
Period of analysis	n	20	years	project lifetime
Discount rate	d	0.10		
Inflation rate	i	0.05		
Discount factor	a	0.954		$a = (1+i)/(1+d)$
Annualised factor	$P_{a(n)}$	12.65		$P_{a(n)} = a(1-a^n)/(1-a)$
2. System specification and performance				
Daily load	L_d	3.586	kWh/day	20 posts
Annual load	L_a	1308.89	kWh/year	$365*L_d$
Solar Module				
Array size	S_a	2800	W_P	20 posts
Module unit price	S_p	6	$\$/W_P$	silicon cells
Lifetime	S_{lt}	20	years	
Battery				
Battery capacity	B_c	48	kWh	existing data
Battery unit price	B_p	150	$/kWh	
Lifetime	B_{lt}	5	years	
Control unit (management unit)				
No. of control unit used	R_t	20	sets	
Control unit price	R_p	70	$/set	
Control unit lifetime	R_{lt}	5	years	
Power Conditioner/Lamp housing				
Inverter & Lamp housing	I_{in}	20	sets	
Inverter & Lamp housing unit price	I_p	40	$/set	
Lifetime	I_{lt}	10	years	
Lamps				
Low pressure sodium lamp	T_l	20	lamps	
Lamp unit price	T_p	25	$/lamp	
Lifetime	T_{lt}	2	years	
Mounting and Foundation				
Mounting & Foundation unit price	K_p	0.5	$\$/W_P$	lifetime 20 years
3. Cost data				
PV array	C_{pv}	16800	$	$C_{pv} = S_a * S_p$
Battery	C_{bat}	7200	$	$C_{bat} = B_c * B_p$
Charge controllers	C_{cc}	1400	$	$C_{cc} = R_t * R_p$
Power conditioner/Lamp housing	C_{pc}	800	$	$C_{pc} = I_{in} * I_p$
Lamp	C_l	500	$	$C_l = T_p * T_{lt}$
Mounting & Foundation	C_{sw}	1400	$	$C_{sw} = S_a * K_p$
Installation (20%)	C_{in}	3360	$	$C_{in} = 0.2*C_{pv}$
a) Capital cost	C_{cap}	**31460**	$	
Operation & Maintenance (2%)	C_{om}	336	$	$C_{om} = 0.02*C_{pv}$
b) Life Cycle O&M Cost	$C_{o\&m}$	**4250.4**	$	$C_{om} * P_{a(n)}$
Replacement Cost	*Yr.(i)*		*PW*	
(i) Battery	5	0.79	5688	$PW = C_{bat} * P_{r(i)}$
	10	0.63	4536	
	15	0.50	3600	
(ii) Charge controllers			2688	every 5 years
(iii) Power conditioner/Lamp housing			504	every 10 years
(iv) Low pressure sodium lamp			3100	every 2 years
c) Life Cycle Replacement Cost	C_{rep}		**20116**	
d) Salvage	C_{sal}		**-0.0**	
4. Economic indicator				
Total Life Cycle Cost	LCC	**55826.4 US$**		LCC = a+b+c+d
Annualised LCC	ALCC	**4413.15 US$/year**		$ALCC = LCC/P_{a(n)}$
Cost of Electricity	COE	**3.37 US$/kWh**		$COE = ALCC/L_a$

5.6 PV System for the Community Facilities in the Village

In low income rural areas, most private households may not be able to afford to connect to a grid supply (without subsidy), and the likely consumers would be community facilities, such as school, clinics or first aid room and recreational room or activity room. When a decentralised stand-alone PV system is designed to supply electrical power for necessary loads in a community centre within a village where is far from utility grid, the selection of high-efficiency appliances and type of loads is important. This is because these loads for public use and the system including replacement costs may come from the annual budget of central government. When these loads meet a failure early, it may be difficult to budget for replacement. The appliances that are suitable for a community centre are lighting, TV set and video. The refrigerator/freezer is considered separately for design (see topic 5.4). Most lighting in the rural areas of developing countries which are far from the national utility grid is provided by candles, kerosene lamps. The light provided is poor quality and low light output. Light intensity is measured in lumens. A reasonable level of illumination for reading may require at least 200 lumens. A candle provides an output of 10 lumens, while a wick (paraffin lamp) can offer 20 lumens. In contrast, a 8 W_P PV light can provide an output of 480 lumens [16,17]. As a result, PV lighting systems can be a cheap way to provide adequate rural lighting. Table 5.8 presents typical sources of light for supplying lighting with PV systems in the rural village.

Table 5.8 The output and power use efficiency

Type of light	Light Output (lumens)	Typical Efficiency (lumens/Watt)
Candle	10-30	0.2
Paraffin lamp (wick)	20-80	0.3
Kerosene lamp (wick)	100	0.4
Torch bulb (3 W)	10	3
Incandescent (40 W)	400	10
Incandescent (60 W)	660	11
Incandescent (100 W)	1750	18
Fluorescent (11 W)	590	58
Fluorescent (18 W)	1100	61
Fluorescent (36 W)	2000	72
HP mercury vapour (80 W)	3700	46
LP sodium vapour (35 W)	4700	134

5.6.1 Criteria for Selecting the Load for the Community Facilities

5.6.1.1 Lighting Load

It is very important to consider the technical characteristic, such as light output, colour temperature, power efficiency and lifetime. In fact, the light output is defined in terms of the luminous flux, namely the amount of light emitted per second in unit solid angle of one steradian by a uniform point source of one candle intensity. It is measured in lumens [18]. Colour temperature is a measure of the spectral distribution of the electromagnetic radiation emitted from the light source. Its unit is degrees Kelvin (K). Lifetime is defined in terms of the number of hours of light output based on a continuous duty cycle of 3 hours ON and twenty minutes OFF.

(1) *Incandescent Lamps*

These are constructed with a tungsten filament inside a thin glass envelope filled with argon or nitrogen (to reduce oxidation or burning of the filament). They are inefficient and last between 500-2000 hours depending on the quality of manufacture. The poor efficiency is due to the high infra-red component of the spectrum compared with the visible component of the spectrum. This means that tungsten incandescent lamps are more effective heaters than light sources. A low voltage incandescent is generally more efficient (up to 40 % more) than a high voltage bulb of the same watt rating due to the higher current through the filament. Conventional incandescent bulbs, such as 40 W, 60 W and 100 W are widely available as regular bayonet or screw mount for use in high voltage (220 VAC) or low voltage (12, 24 VDC) systems.

(2) *Fluorescent Lamps*

Standard fluorescent light is the double-ended tube light that can be found in many places. Fluorescent lamps are the usual choice for PV lighting systems because of their higher efficacy. They provide a whiter light a incandescent lamps. At present, they are among the most reliable and cost effective models available in low voltage fluorescent lighting (12,24 VDC) and are suitable for a great number of applications, particularly in PV lighting systems. The overall efficiency is better than that of tungsten lamps. Some small fluorescent lamps include a built-in inverter, and often run at a higher frequency than the mains, which improves the light's efficiency. Fluorescent lamps can produce visible light in different colours depending on the colour temperature, for example at 3000 K (warm white), 3500 K (white), 4000 K (cool white) and 6000 K (daylight). Tube configuration ranges of 8,11,18 and 36 W are the most popular sizes and are widely available in many rural shops of Thailand.

(3) ***High or Low Pressure Gas Discharge Lamps***

High pressure mercury or low pressure sodium gas discharge lamps are mainly used for outdoor high mast lighting because they operate at a wavelength close to the peak sensitivity of the human eye and emit a golden-white light. These lamps provide the highest luminous efficiency of any general purpose lamp. They are particularly suitable for use where long operation hours are required. Low pressure sodium lamps are most widely used with the range of 18,26 and 35 W. The system voltage operating is 12, 24 VDC.

5.6.1.2 *Television and Video Loads*

Television and video are largely used for educational purposes. Educational applications for schools, adult education, literacy, vocational training, health education and environmental education are essential in facilitating development. These may rely on broadcast programmes or on recorded material. In addition, they are able to be used for recreational activity during night time. Although they are designed as AC appliances, they operate from an internal, regulated, low voltage DC power supplies to power the electronic circuits and a separate high frequency, high voltage supply to the screen. A transformer and rectifier are employed to bring the AC source power down to the regulated internal DC power requirements. The DC power requirements have been reduced to 5-18 W for Black and White (B/W) television and 60-120 W for colour television. Typical videos have a relatively low operating power requirement of between 20-50 W.

5.6.2 Design of a PV System for the Community Facilities in the Sample Village

GENERAL CONSIDERATIONS

Application :	Lighting and electrical appliances in a community centre
Site :	Udon Thani, Thailand
Location :	17.3° N, 102.8° E
Environment :	High Plains
Maximum Wind Speed:	5.9 m/s (at 600 m height)
Load :	Fluorescent Lamp, TV and VCR

ARRAY :

PV array should be located close to the loads and batteries to reduce power loss. The array frame should be grounded and the array azimuth should be true south with tilt angle. All wiring should be laced and attached to the support structure. All connections should be in water-tight junction boxes with strain relief connector.

CONTROLLER :

The charge controller is a crucial device to prevent deep discharge and overcharge of the battery. For systems installed in remote areas, the charge regulation is critical and directly affects life-cycle-cost. If multiple lamps are to be operated, it must have the capability of lighting all at the same time.

BATTERIES :

Deep cycle lead-acid type specifically designed is recommended because it can be widely purchased in many rural areas of Thailand. It is less expensive than nickel-cadmium types. Batteries should be located in a weather resistant enclosure. If liquid electrolyte batteries are used, nonmetallic enclosures are recommended to prevent corrosion. Each parallel string of batteries should be protected by a fuse installed at the battery output terminal.

INVERTER :

The selection of an inverter is a critical decision in remote areas, for a community centre usually has AC loads, for example, TV and video cassette recorder. If these AC loads are used, the inverter must be suitably sized and be capable of starting and operating the expected loads that run at the same time.

LOAD :

Use fluorescent lamps instead of incandescent lamps, because they are 4-5 times more efficient than incandescent lamps. Large loads, such as washing machines, vacuum cleaner and ceiling fans should be avoided. As a general rule, use a 12 VDC system for demand less than 500 W. When the AC loads are less than 1500 W, a 12 VDC system with inverter is typically selected. A 24 VDC system should be considered for AC loads (220 V) in the 2.5-5 kW range.

WIRING/SWITCH GEAR :

All wiring, fusing should conform to standard electrical procedure. Selecting a suitable size of fuse is critical to protect all system components from damage due to short circuit current or over current flows.

MOUNTING :

Ground mounting offers ease of installation and maintenance and the possibility of seasonal adjustment of tilt angle. However, a PV fixed array is also recommended with an optimum tilt angle of a latitude degree. PV array should be mounted in an area clear from shading.

Worksheet #1	Calculation of the daily load demand												
Load description	DC or AC	No. of sets	Load current (A)	Load voltage (V)	DC power (W)	AC power (W)	Daily duty cycle (h/day)	Weekly duty cycle (d/week)	7 days in a week	Power conversion eff. (decimal)	Energy requirement (Wh/day)	Nominal system voltage (V)	Ampere hour load (Ah/day)
			×	×	=	=	×	×	÷	÷	=	÷	=
Fluorescent (36W)	*DC*	*10*	*2.6*	*12*	*312*	-	*5*	*7*	*7*	*1*	*1560*	*12*	*130*
TV	*AC*	*1*	*0.545*	*220*	-	*120*	*5*	*7*	*7*	*0.85*	*705.88*	*12*	*58.82*
VCR	*AC*	*1*	*0.182*	*220*	-	*40*	*5*	*7*	*7*	*0.85*	*235.30*	*12*	*19.60*
Total DC load power (W)					***312***	***160***	**Total AC load power (W)**			Total Wh/day	***2501.18***	Total Ah/day	*208.42*

Design Notes

1) *Load current for fluorescent lamp is based on company's technical data sheet # BL36 (Lab Craft)*

Maximum Tilt Angle Worksheet # 2	Estimate The Maximum Tilt Angle (for Community Centre System)

Site : *Udon Thani of Thailand* **Latitude :** *17.38 °N* **Longitude :** *102.72 °E*

Tilt at latitude - 25°

Month	Ampere-hours load (Ah/day)		Peak sun (h/day)		Current (A)
Jan.	*208.42*	÷	*5.773*	=	*36.10*
Feb.	*208.42*	÷	*4.780*	=	*43.60*
Mar.	*208.42*	÷	*3.969*	=	*52.51*
Apr.	*208.42*	÷	*4.105*	=	*50.77*
May	*208.42*	÷	*3.392*	=	*61.44*
Jun.	*208.42*	÷	*3.508*	=	*59.41*
Jul.	*208.42*	÷	*3.166*	=	*65.83*
Aug.	*208.42*	÷	*3.233*	=	*64.46*
Sep.	*208.42*	÷	*4.003*	=	*52.06*
Oct.	*208.42*	÷	*4.543*	=	*45.87*
Nov.	*208.42*	÷	*4.898*	=	*42.55*
Dec.	*208.42*	÷	*5.400*	=	*38.59*

Select the largest current and corresponding peak sun

latitude - 25°	
peak sun (h/day)	current (A)
3.166	*65.83*

Tilt at latitude

Month	Ampere-hours load (Ah/day)		Peak sun (h/day)		Current (A)
Jan.	*208.42*	÷	*5.317*	=	*39.20*
Feb.	*208.42*	÷	*4.737*	=	*43.99*
Mar.	*208.42*	÷	*4.246*	=	*49.08*
Apr.	*208.42*	÷	*4.714*	=	*44.21*
May	*208.42*	÷	*4.105*	=	*50.77*
Jun.	*208.42*	÷	*4.407*	=	*47.29*
Jul.	*208.42*	÷	*3.859*	=	*54.01*
Aug.	*208.42*	÷	*3.773*	=	*55.24*
Sep.	*208.42*	÷	*4.409*	=	*47.27*
Oct.	*208.42*	÷	*4.617*	=	*45.14*
Nov.	*208.42*	÷	*4.642*	=	*44.89*
Dec.	*208.42*	÷	*4.918*	=	*42.38*

latitude	
peak sun (h/day)	current (A)
3.773	*55.24*

Tilt at latitude + 25°

Month	Ampere-hours load (Ah/day)		Peak sun (h/day)		Current (A)
Jan.	*208.42*	÷	*4.104*	=	*50.78*
Feb.	*208.42*	÷	*4.065*	=	*51.27*
Mar.	*208.42*	÷	*4.001*	=	*52.09*
Apr.	*208.42*	÷	*4.805*	=	*43.37*
May	*208.42*	÷	*4.385*	=	*47.56*
Jun.	*208.42*	÷	*4.856*	=	*42.92*
Jul.	*208.42*	÷	*4.164*	=	*50.05*
Aug.	*208.42*	÷	*3.904*	=	*53.38*
Sep.	*208.42*	÷	*4.272*	=	*48.78*
Oct.	*208.42*	÷	*4.089*	=	*50.97*
Nov.	*208.42*	÷	*3.755*	=	*55.5*
Dec.	*208.42*	÷	*3.744*	=	*55.66*

latitude + 25°	
peak sun (h/day)	current (A)
3.744	*55.66*

Now select the latitude angle that give the smallest current and corresponding peak sun from each latitude and enter on the right hand side

peak sun (h/day)	current (A)
3.773	*55.24*
Max. tilt angle selected	
17°	

Note : This angle is for fixed tilt angle throughout the year

Design Notes:

Community Centre System Worksheet # CCS	**Calculation of PV Array and Battery Sizing**
Site : *Udon Thani, Thailand* Daily load : *208.42* Ah/day Tilt angle : *17* degrees Monthly mean daily solar radiation: *3.773* kWh/m^2 Availability required : *Critical Design*	Battery efficiency : *85 %* Max. DOD : *70 %* Regulator efficiency : *85 %* Line loss factor : *5 %* Nominal system voltage : *12* VDC

1) PV Array Sizing

Ampere-hours load (Ah/day)		Regulator efficiency (decimal)		Battery efficiency (decimal)		Line loss factor (decimal)		Corrected ampere-hours (Ah day)
208.42	÷	*0.85*	÷	*0.85*	÷	*0.95*	=	*303.65*

Corrected ampere-hours (Ah/day)		Peak sun hours at selected tilt angle (h/day)		Module degradation factor (decimal)		Corrected array current (A)
303.65	÷	*3.773*	÷	*0.9*	=	*89.42*
				Rated current of a PV module	÷	*4.72*
				Number of modules connected in parallel	=	*(18.9) ~ 19*

Nominal system voltage (V)		Nominal voltage of a PV module (V)		No. of modules connected in series		No. of modules connected in parallel		Total number of modules used
12	÷	*12*	=	*1*	×	*19*	=	*19*

2) Battery Sizing

Corrected ampere-hours (Ah/day)		Days of autonomy (day)		Max. depth of discharge (decimal)		Corrected battery capacity (Ah)		Each battery capacity (Ah)		No. of batteries connected in parallel
303.65	×	*5*	÷	*0.7*	=	*2168.92*	÷	*120*	=	*18*

Nominal system voltage (V)		Nominal battery voltage (V)		No. of batteries connected in series		No. of batteries connected in parallel		Total number of batteries used
12	÷	*12*	=	*1*	×	*18*	=	*18*

PV module information		**Battery information**
Manufacturer : *BP Solar*		Manufacturer : *BP Solar*
Model : *BP585F*		Model : *L120*
Type : *monocrystalline silicon (36 series cells)*		Type : *Lead-Acid, Deep Cycle*
SC current : *5* A	OC voltage : *22.3* V	Nominal voltage : *12* V
Max. current : *4.72* A_{mp}	Max. voltage : *18* V_{mp}	Capacity : *120* Ah

Design Notes :

Charge Controller General Worksheet # CC		Technical Specifications of Charge Controller								
Short circuit current of a module (A)		No. of modules connected in parallel		Safety factor		Design controller capacity (A)		Each rated ampere of controller (A)		No. of controllers in parallel
5	×	*19*	×	**1.25**	=	*118.75*	÷	*120*	=	*1*

Manufacturer : *EnerMaxer*
Regulator Type : *20-944*
System voltage (V) : *12*
Maximum load current (A) :
Operating temperature (°C) :
Fuse rating (A) :
Disconnection pre-warning :
Disconnection level :
Reconnection level :

Metering and protection

Voltage : ✓❑ Yes ❑ No
Current : ✓❑ Yes ❑ No
State of Charge (SOC) : ✓❑ Yes ❑ No
Under and Overvoltage : ✓❑ Yes ❑ No
Over-temperature, load current : ✓❑ Yes ❑ No
Others : LED display for charge control and over-discharge protection

Design Notes :

1) It provides charging sources constant voltage, pulse width modulation charging. The float set-point is easily adjustable with a front panel knob.

Power Conditioning General Sheet # PC		Power Conditioning Unit Specification Sheet					
Inverter							
Total AC power load (W)		Power conversion efficiency (decimal)		Safety factor		Minimum inverter size wattage (W)	Round up next inverter size (W)
160	÷	*0.85*	×	**1.25**	=	*235.29*	*250*

Manufacture : *MASTERVOLT*
Inverter model no. : *12/200*
Output waveform : *sine wave*
Nominal input voltage (VDC) : *12*
Output voltage (VAC) : *230*
Frequency regulation (H_z) : *50*
Nominal power (W) : *250*
Maximum load AC current (A) : *N/A*
Efficiency (%) : *85*

Design Notes :

Total AC loads are run at the same time and this inverter is for TV and VCR.

Converter

System Requirement	
Input DC voltage :	VDC
Output DC voltage :	VDC
Output power :	W
Converter Designed	
Manufacturer :	
Model :	
Input voltage :	VDC
Output voltage :	VDC
Output current :	A

Converter is not needed for this system, thus do not complete this section.

Protection of System Components General Worksheet # PSC	Protection of System Components

Array Description

Short circuit current of a module (A)		No. of modules connected in parallel		Total array short circuit current (A)		Safety factor		Rated current of protective device (A)
5	×	*19*	=	*95*	×	**1.25**	=	*118.75*

Controller / Main Load Description

Total DC load power (W)		Nominal system voltage (V)		Maximum DC load current (A)		Safety factor		Rated current of protective device (A)
312	÷	*12*	=	*26*	×	**1.25**	=	*32.5*

Battery Description

Maximum current of a module (A)		No. of modules connected in parallel		Peak current from PV array (A)		Safety factor		Rated current of protective device (A)
4.72	×	*19*	=	*89.68*	×	**1.25**	=	*112*

Inverter Description

Total AC load power (W)		Nominal system voltage (V)		Power factor (decimal)		Safety factor		Rated current of protective device (A)
160	÷	*220*	÷	*0.85*	×	**1.25**	=	*1.07*

Branch Circuit # 1 (Fluorescent)					Branch Circuit # 2 (TV & VCR)				
Rated load current (A)		Safety factor		Rated current of protective device (A)	Rated load current (A)		Safety factor		Rated current of protective device (A)
26	×	**1.25**	=	*32.5*	*(0.54+0.18) 0.72*	×	**1.25**	=	*0.90*

Branch Circuit # 3 (specify)					Branch Circuit # 4 (specify)				
Rated load current (A)		Safety factor		Rated current of protective device (A)	Rated load current (A)		Safety factor		Rated current of protective device (A)
	×	**1.25**	=	*N/A*		×	**1.25**	=	*N/A*

Circuit	Protective Device (No. of Devices) CB	Fuse	Switch	Surge	Rated Current (A)	Rated Voltage (V)	Descriptions
Array to controller		*2*			*125*	*380*	*HBC fuse*[1]
Controller to battery			*1*		*120*	*250*	*Disconnect SW*[2]
Controller to inverter	*1*				*10*	*250*	*MCB*[3]
Controller to DC load	*1*				*40*	*250*	"
Inverter to AC load		*1*			*2*	*250*	*Cartridge type*[4]

Design Notes:

1) *High Breaking Capacity fuse 120 kA at 380 V with leaf spring fuse blown including a fuse base.*
2) *Fusible models use standard class R cartridge fuses, enclosure is NEMA 1 for indoor use and includes 2 fuses 120 A rated.*
3) *Moulded Circuit Breaker with double poles and surface mounting type, breaking capacity 6 kA*
4) *Fuse with fuse-holder 10 A rated.*

DC Wring General Worksheet # DCW	DC Wire Sizing Specification				
Descriptions	System voltage (V)	Maximum current (A)	Allowable voltage drop (%)	Wire size (mm^2)	Wire type
Array Circuit					
Module to Module	*12*	*5*	*2*	*2.5*	*THW*
Array to Control Building					
Array to Controller	*12*	*118.75*	*2*	*35*	*THW*
DC Circuits					
Battery to Battery					
Regulator to battery	*12*	*112*	*2*	*35*[1]	*THHN (battery cable)*
Regulator to DC load	*12*	*32.5*	*2*	*4*	*THW*
Regulator to inverter	*12*	*0.90*	*2*	*2.5*	*THW*
Branch Circuit					
1. *lighting per lamp*	*12*	*2.6*	*3*	*1.5*	*THW*
2.					
3.					
4.					
5.					
System Grounding	Wire Size (mm^2)		Wire Type		Type of Earth Ground
Equipment Ground					
System	*6*		*bare copper*		*to ground rod*

Design Notes:

1) Base on the company's technical data sheet.

AC wiring General Worksheet # ACW	AC Wire Sizing Specification				
Description	System voltage (V)	Maximum current (A)	Allowable voltage drop (%)	Wire size (mm^2)	Wire type
AC Circuit					
Inverter to AC load	*220*	*0.90*	*3*	*2.5*	*THW*
AC Power Distribution line					
Branch Circuit					
1. *TV*	*220*	*0.54*	*3*	*1.5*	*THW*
2.. *Video*	*220*	*0.18*	*3*	*1.5*	*THW*
3.					
4.					
5.					
System Grounding	Wire Size (mm^2)		Wire Type		Type of Earth Ground
Equipment Ground	-		-		-
system	-		-		-

Design Notes:

5.6.3 Life Cycle Cost Analysis of a PV System for the Community Facilities

Table 5.9 Life cycle cost analysis of a PV system for the community facilities

Project/Site : Udon Thani, Thailand	Type of system : PV community facilities			
1. Financial parameters	*Symbol*	*Values*	*Unit*	*Remark*
Period of analysis	n	20	years	project lifetime
Discount rate	d	0.10		
Inflation rate	i	0.05		
Discount factor	a	0.954		a = (1+i)/(1+d)
Annualised factor	$P_{a(n)}$	12.65		$P_{a(n)} = a(1-a^n)/(1-a)$
2. System specification and performance				
Daily load	L_d	2.5	kWh/day	
Annual load	L_a	912.5	kWh/year	$365*L_d$
Solar Module				
Array size	S_a	1615	W_p	existing data
Module unit price	S_p	6	$\$/W_p$	silicon cells
Lifetime	S_{lt}	20	years	
Battery				
Battery capacity	B_c	25.92	kWh	existing data
Battery unit price	B_p	150	$/kWh	
Lifetime	B_{lt}	5	years	
Controller				
Charge controller price		600	$	
Controller lifetime		5	years	
Power Conditioner				
Inverter price		200	$	
Lifetime		10	years	
End-user loads				
Lamp unit price		50	$	10 sets
Lifetime		20	years	
TV and VCR		400	$	
Lifetime		10	years	
Mounting and Foundation				
Mounting & Foundation unit price	K_p	0.5	$\$/W_p$	
Lifetime	K_{lt}	20	years	
3. Cost data				
PV array	C_{pv}	9690	$	$C_{pv} = S_a * S_p$
Battery	C_{bat}	3888	$	$C_{bat} = B_c * B_p$
Charge controllers		600	$	
Power conditioner		200	$	
Fluorescent lamp		50	$	
TV and VCR		400	$	
Mounting & Foundation	C_{sw}	807.5	$	$C_{sw} = S_a * K_p$
Installation (20%)	C_{in}	1938	$	$C_{in} = 0.2*C_{pv}$
a) Capital cost	C_{cap}	**17573.5**	$	
Operation & Maintenance (2%)	C_{om}	193.8	$	$C_{om} = 0.02*C_{pv}$
b) Life Cycle O&M Cost	$C_{o\&m}$	**2451.57**	$	$C_{om} * P_{a(n)}$
Replacement Cost	*Yr.(i)*		*PW*	
(i) Battery			7465	every 5 years
(ii) Charge controllers			1152	every 5 years
(iii) Power conditioner			126	every 10 years
(iv) Fluorescent lamp			310	every 2 years
(v) TV and VCR			252	every 10 years
c) Life Cycle Replacement Cost	C_{rep}		**9305**	
d) Salvage	C_{sal}		**-0.0**	
4. Economic indicator				
Total life Cycle Cost	LCC	**29330.07 US$**		LCC = a+b+c+d
Annualised LCC	ALCC	**2318.58 US$/year**		$ALCC = LCC/P_{a(n)}$
Cost of Electricity	COE	**2.54 US$/kWh**		$COE = ALCC/L_a$

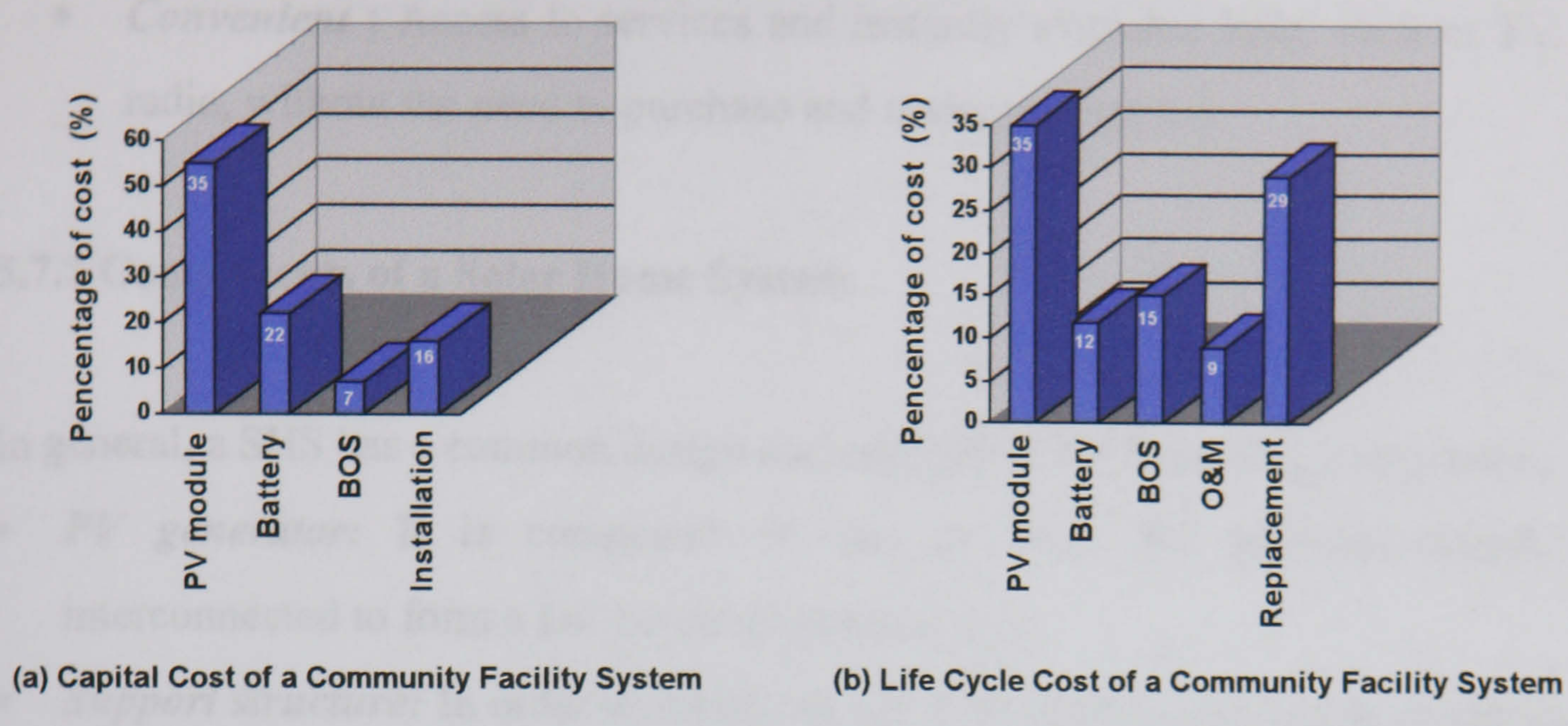


Figure 5.14 Cost elements of a community facility system

5.7 Solar (PV) Home Systems

In a rural area which has no electricity supply, people use candles, kerosene and car batteries to provide the lighting and other services that they really want. Most, if not all, of these can also be met by using the solar home system (SHS). Over the past decade, considerable experience has been gained in designing and implementing SHS programmes in remote areas [19]. The current costs of PV systems make them an economical option in situations, firstly, where conventional power is too expensive for the small amount of power required and, secondly, where the supply must be reliable, such as vaccine refrigerators in rural health centres or in areas that are too remote or geographically isolated for grid connection.

5.7.1 Advantage of a SHS over Kerosene Lighting and Rechargeable Battery

- ***Cleaner indoor air:*** Due to reduced (or eliminated) soot and fumes from kerosene and candles
- ***Higher quality light*:** Both in lumen output and colour rendering ability, making such tasks as reading and studying easier.
- ***Improved safety level*** **:** The SHS eliminates dangers from accidental fires and burns from kerosene devices, candles or acid spills from batteries.
- ***Development*** **:** To elevate social status associated with rural electrification.

- ***Reliability*** : Greater reliability and freedom from fuel need.
- ***Convenient*** : Access to services and instantly available light, such as TV and radio, without the need to purchase and transport supplies.

5.7.2 Components of a Solar Home System

In general, a SHS has a common design and consists of the following components:

- ***PV generator:*** It is composed of one or more PV modules which are interconnected to form a DC power producing unit.
- ***Support structure:*** In order to install one or more modules on a pole mounting or roof mounting, the support structures are needed.
- ***Battery:*** It consists of several cells.
- ***Charge regulator:*** It is used for protection of the battery from damage due to over charging and excessive discharging.
- ***Loads:*** Typical loads in SHS are lamps (fluorescent, or incandescent), a radio and a black and white TV set. These loads are widely used in many developing countries where SHS have been installed.
- ***Wiring:*** It includes the installation of light fixtures, electric plug, switch and any connection boxes.

The main components of a SHS is depicted in Figure 5.15. A typical SHS needs power from a PV module between 20 W_P and 100 W_P depending on the size of the load. At present, most SHSs are lower than 100 W_P and entirely direct current [20]. Both the array size and the sunlight availability will determine the amount of electricity available for daily use. In a country, such as Indonesia (it is now the leading country for SHS dissemination), a 50 W_P system can adequately provide power to operate two small (6 and 10W) fluorescent lamps, a small black and white TV (10W) and a radio (6W) for up to 5 hours. SHS can also help households generate income from business activities [21].

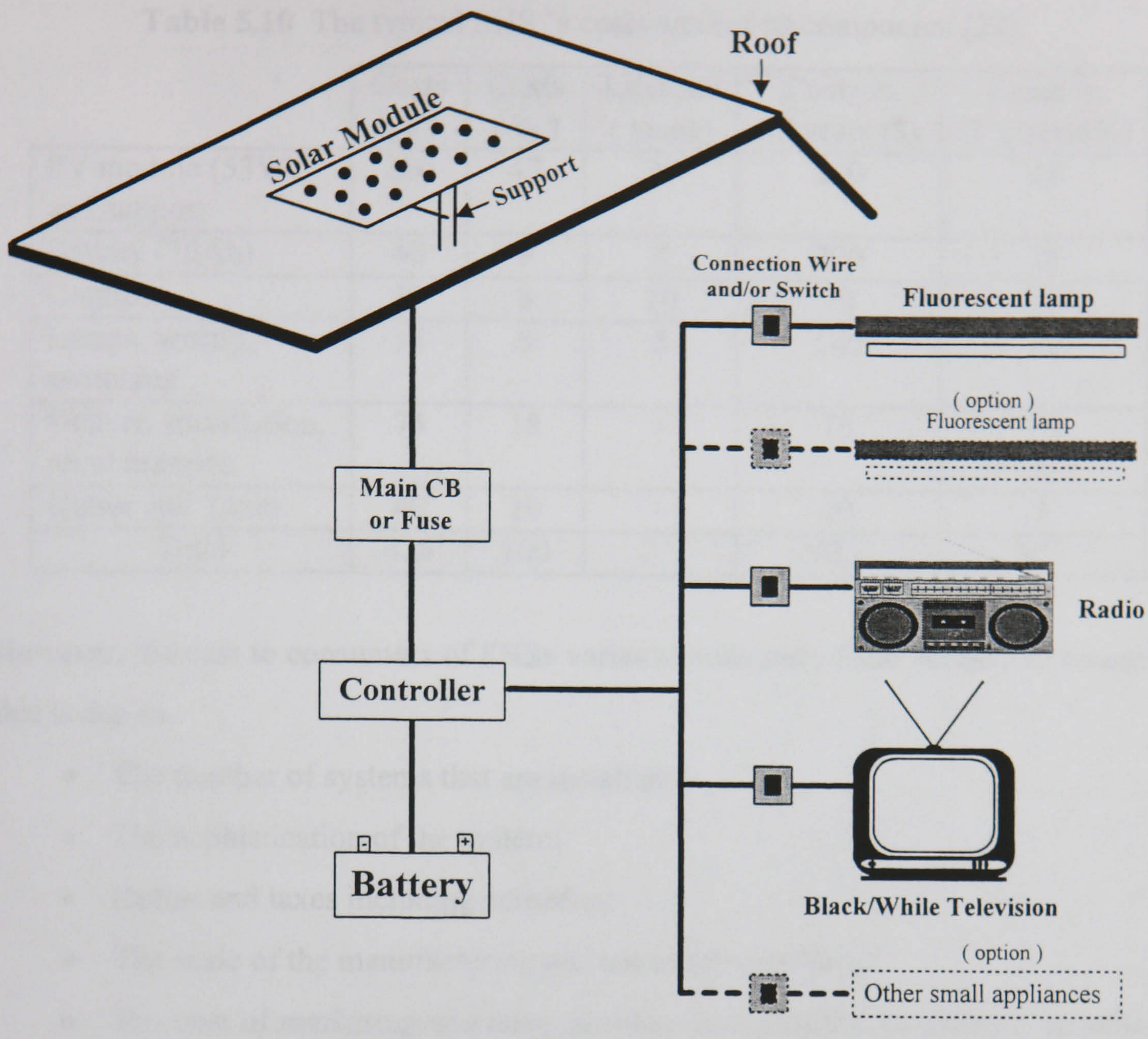


Figure 5.15 A typical solar home system.

5.7.3 The Cost of a SHS

At present, the cost of a SHS may vary between US$ 425 and US$1500, depending on the size of market, import duties and taxes, and the share of local production of the components. The costs of the SHS have a clear advantage over the costs for conventional electric grid extension, reported to be between $400 and $600 per household under the most favorable conditions in densely populated areas in Asia [22] and which may go up to several thousand dollars elsewhere. The typical costs of the SHS and its components are given in Table 5.10. They are given for the situation in Indonesia based on annual sales of 5000 to 6000 SHSs per manufacture and moderate assumptions for future price reduction. Maintenance cost is not included.

Table 5.10 The typical SHS 's costs against its component [22].

	Costs ($)	Costs (%)	Lifetime (years)	Costs in 20 years ($)	Costs in 20 years (%)
PV module (53W) and support	200	47	20	200	28
Battery (70Ah)	40	9	4	200	28
Controls	35	8	10	70	10
Lamps, wiring, switching	35	8	5	140	19
Deliver, installation, retail margins	75	18	-	75	10
Duties and Taxes	40	10	-	40	5
Total	425	100		725	100

However, the cost to consumers of SHSs varies significantly from country to country, this is due to :

- The number of systems that are installed;
- The sophistication of the system;
- Duties and taxes including subsidies;
- The scale of the manufacturing and assembly processes;
- The cost of marketing and other services including the number of "re-seller" steps in the distribution chain;
- The cost of funds for working capital and capital investments;
- Capacity utilisation in manufacture, sales and service, and
- The degree of competition in the marketplace.

5.7.4 Design of a Solar Home System in the Sample Village

The size of a SHS depends on factors such as daily load requirement, efficiency of system parameters, average daily insolation at design location and days of autonomy for battery during the worst month of the year [10,11,23]. By reducing the amount of power used for lighting, the householder can also use a small B/W TV Hence, the household loads assumed in this design are slightly changed from those in Table 4.3. They consist of a radio (6W) and a fluorescent lamp (8W) that are both used for 2 hours/day, and a fluorescent lamp (18W) and a small B/W TV (10W) that are both used for 3 hours/day. All loads are operated at 12 VDC.

GENERAL CONSIDERATIONS

Application :	Solar Home System
Site :	Udon Thani, Thailand
Location :	17.3° N, 102.8° E
Environment :	High Plains
Maximum Wind Speed :	5.9 m/s (at 600 m height)
Load :	Fluorescent, radio and B/W TV

ARRAY :

PV modules should be located close to the loads and battery to reduce power loss. Basically, a PV module used in a solar home system can be mounted on a pole above the roof level and wire to a charge controller, a battery and loads. The module azimuth should be true south with tilt angle. All wiring should be laced and attached to the support structure. A module pole must be kept away from any high trees to avoid shading.

CONTROLLER :

It is a very important to install a charge controller in each household to prevent deep discharge and overcharge of the battery. The battery lifetime could be reduced significantly if the battery is discharged over a limited value. It is strongly recommended that a voltage regulator must be installed in each household to prevent deep discharge of the battery.

BATTERIES :

Deep cycle lead-acid type specifically designed is recommended for use in each household because it is widely available in many rural shops of Thailand. If liquid electrolyte batteries are used, nonmetallic enclosures are recommended to prevent corrosion. Users must carefully abide by the manual of users, especially for maintenance of the battery because lack of periodic maintenance is one of the main factors to shorter battery lifetime.

INVERTER :

DC loads are usually recommended for a solar home system. It is also possible for solar home systems to supply AC power by using an inverter. The selection of an inverter is a critical decision in remote areas, the inverter must be suitably sized and capable of starting and operating the expected loads that run at the same time.

LOAD :

Use fluorescent lamps instead of incandescent lamps, because they are 4-5 times more efficient than incandescent lamps. Large loads, such as washing machines, vacuum cleaner and ceiling fans should be avoided. In general, use a 12 VDC system for demand less than 500 W. When the AC loads are less than 1500 W, a 12 VDC system with inverter is typically selected. A 24 VDC system should be considered for AC loads (220 V) in the 2.5-5 kW range.

WIRING/SWITCH GEAR :

All wiring should be colour coded and fusing should conform to standard electrical procedures. Selecting a suitable size of fuse is critical to protect all system components from damage due to short circuit current or over current flows. It is recommended that the cable sizes wired from a PV module to the charge controller should be 2.5 mm^2 and from the charge controller to the battery should be 4 mm^2 or more. Fuse should preferably be installed in the positive line.

MOUNTING :

Support structures must be mounted to allow easy access for PV module cleaning and connecting box inspections and must be mounted such that their resistances to corrosion, fatigue and wind are preserved. Pedestal and wall mountings normally allow easy access to the PV modules without risking the water tightness of the roof. Lamp lenses, cover grids, etc. (if used) must be insect proof.

Worksheet #1	Calculation of the daily load demand												
Load description	DC or AC	No. of sets	Load current (A)	Load voltage (V)	DC power (W)	AC power (W)	Daily duty cycle (h/day)	Weekly duty cycle (d/week)	7 days in a week	Power conversion eff. (decimal)	Energy requirement (Wh/day)	Nominal system voltage (V)	Ampere hour load (Ah/day)
			×	×	=	=	×	×	÷	×	=	÷	=
Radio 6 w	*DC*	*1*	*0.5*	*12*	*6*	*N/A*	*2*	*7*	*7*	*1.00*	*12.0*	*12*	*1.00*
Fluorescent 8 w	*DC*	*1*	*0.8*	*12*	*9.6*	*N/A*	*2*	*7*	*7*	*1.00*	*19.2*	*12*	*1.60*
Fluorescent 18 w	*DC*	*1*	*1.8*	*12*	*21.6*	*N/A*	*3*	*7*	*7*	*1.00*	*64.8*	*12*	*5.40*
Black/White TV 17″(10 w)	*DC*	*1*	*0.95*	*12*	*11.40*	*N/A*	*3*	*7*	*7*	*1.00*	*34.2*	*12*	*2.85*
Total DC power load (W)					***48.6***	***N/A***	**Total AC power load (W)**			**Total Wh/day**	***130.20***	**Total Ah/day**	***10.85***

Design Notes

1) *This worksheet is based on daily load requirement for a solar home system in each household in the sample village.*

Maximum Tilt Angle Worksheet # 2	**Estimate The Maximum Tilt Angle (for Solar Home System)**

Site : *Udon Thani of Thailand* **Latitude :** *17.38°N* **Longitude :** *102.72°E*

Month	Ampere-hours load (Ah/day)		Peak sun (h/day)		Current (A)	Select the largest current and corresponding peak sun	
Tilt at latitude - 25°							
Jan.	*10.85*	÷	*5.773*	=	*1.88*		
Feb.	*10.85*	÷	*4.780*	=	*2.27*		
Mar.	*10.85*	÷	*3.969*	=	*2.73*		
Apr.	*10.85*	÷	*4.105*	=	*2.64*		
May	*10.85*	÷	*3.392*	=	*3.20*	latitude - 25°	
Jun.	*10.85*	÷	*3.508*	=	*3.09*	peak sun	current
Jul.	*10.85*	÷	*3.166*	=	*3.42*	(h/day)	(A)
Aug.	*10.85*	÷	*3.233*	=	*3.35*	*3.166*	*3.42*
Sep.	*10.85*	÷	*4.003*	=	*2.71*		
Oct.	*10.85*	÷	*4.543*	=	*2.38*		
Nov.	*10.85*	÷	*4.898*	=	*2.21*		
Dec.	*10.85*	÷	*5.400*	=	*2.01*		
Tilt at latitude							
Jan.	*10.85*	÷	*5.317*	=	*2.04*		
Feb.	*10.85*	÷	*4.737*	=	*2.29*		
Mar.	*10.85*	÷	*4.246*	=	*2.55*		
Apr.	*10.85*	÷	*4.714*	=	*2.30*		
May	*10.85*	÷	*4.105*	=	*2.64*	latitude	
Jun.	*10.85*	÷	*4.407*	=	*2.46*	peak sun	current
Jul.	*10.85*	÷	*3.859*	=	*2.81*	(h/day)	(A)
Aug.	*10.85*	÷	*3.773*	=	*2.87*	*3.773*	*2.87*
Sep.	*10.85*	÷	*4.409*	=	*2.46*		
Oct.	*10.85*	÷	*4.617*	=	*2.35*		
Nov.	*10.85*	÷	*4.642*	=	*2.33*		
Dec.	*10.85*	÷	*4.918*	=	*2.20*		
Tilt at latitude + 25°							
Jan.	*10.85*	÷	*4.104*	=	*2.64*		
Feb.	*10.85*	÷	*4.065*	=	*2.67*		
Mar.	*10.85*	÷	*4.001*	=	*2.71*		
Apr.	*10.85*	÷	*4.805*	=	*2.26*		
May	*10.85*	÷	*4.385*	=	*2.47*	latitude + 25°	
Jun.	*10.85*	÷	*4.856*	=	*2.23*	peak sun	current
Jul.	*10.85*	÷	*4.164*	=	*2.60*	(h/day)	(A)
Aug.	*10.85*	÷	*3.904*	=	*2.78*	*3.744*	*2.90*
Sep.	*10.85*	÷	*4.272*	=	*2.54*		
Oct.	*10.85*	÷	*4.089*	=	*2.65*		
Nov.	*10.85*	÷	*3.755*	=	*2.89*		
Dec.	*10.85*	÷	*3.744*	=	*2.90*		

Now select the latitude angle that give the smallest current and corresponding peak sun from each latitude and enter on the right hand side

Note : This angle is for fixed tilt angle throughout the year

peak sun (h/day)	current (A)
3.773	*2.87*
Max. tilt angle selected	
17°	

Design Notes :

Solar Home System (Worksheet # SHS)	Calculation of PV Array and Battery Sizing

Site : *Udon Thani of Thailand*	Battery efficiency : 85%
Daily load : *10.85* Ah/day	Max. DOD : 70%
Tilt angle : *17* degrees	Regulator efficiency : 85%
Monthly mean daily solar radiation : *3.773* kWh/m^2	Line loss factor : 5%
Availability Required : *Critical Design*	Nominal system voltage : *12* VDC

1) PV Array Sizing

Ampere-hour load (Ah/day)		Regulator efficiency (decimal)		Battery efficiency (decimal)		Line loss factor (decimal)		Corrected ampere-hour (Ah/day)
10.85	÷	*0.85*	÷	*0.85*	÷	*0.95*	=	*15.81*

Corrected ampere-hour (Ah/day)		Peak sun hours at selected tilt angle (h/day)		Module degradation factor (decimal)		Corrected array current (A)
15.81	÷	*3.773*	÷	*0.90*	=	*4.65*
				Rated current of a PV module	÷	*4.72*
				Number of modules connected in parallel	=	*(0.98) ~ 1*

Nominal system voltage (V)		Nominal voltage of a PV module (V)		No. of modules connected in series		No. of modules connected in parallel		Total no. of modules used (modules)
12	÷	*12*	=	*1*	×	*1*	=	*1*

2) Battery Sizing

Corrected ampere-hour (Ah/day)		Days of autonomy (days)		Max. depth of discharge (decimal)		Corrected battery capacity (Ah)		Each rated battery (Ah)		No. of batteries connected in parallel
15.81	×	*5*	÷	*0.70*	=	*112.92*	÷	*120*	=	*(0.94) ~ 1*

Nominal system voltage (V)		Nominal battery voltage (V)		No. of batteries connected in series		No. of batteries connected in parallel		Total number of batteries used
12	÷	*12*	=	*1*	×	*1*	=	*1*

PV module information		Battery information
Manufacturer : *BP Solar*		Manufacturer : *BP Solar*
Model : *BP585*		Model : *L120*
Type : *monocrystalline silicon (36 series cells)*		Type : *Lead-Acid Deep Cycle*
SC current : *5* A	OP voltage : *21.4* V	Nominal voltage : *12* V
Max. current : *4.72* A_{MP}	Max. voltage : *17* V_{MP}	Capacity : *120* Ah

Design Notes :

Charge Controller General Worksheet # CC	Technical Specifications of Charge Controller									
Short circuit current of a module (A)		No. of modules connected in parallel		Safety factor		Design controller capacity (A)		Each rated ampere of controller (A)		No. of controllers in parallel
5	×	*1*	×	**1.25**	=	*6.25*	÷	*8*	=	*(0.78) ~ 1*

Manufacturer : *BP Solar*
Regulator Type : *GCR-800(m)*
System voltage (V) : *12*
Maximum load current (A) : *8*
Operating temperature (˚C) : *-25 ℃ to 50 ℃*
Disconnection pre-warning : *SOC<40% (11.7)*
Disconnection level : *SOC<30% (11.1)*
Reconnection level : *SOC>50% (12.6)*

Metering and protection

Voltage : ✓❑ Yes ❑ No
Current : ✓❑ Yes ❑ No
State of Charge (SOC) : ✓❑ Yes ❑ No
Under and Overvoltage : ✓❑ Yes ❑ No
Over-temperature, load current : ✓❑ Yes ❑ No
Others : LED display for charge control and over-discharge protection

Design Notes :

Regulator must be provided with suitable mounting brackets or/and fixing.

Protection of System Components General Worksheet # PSC	**Protection of System Components**

Array Description								
Short circuit current of a module (A)		No. of modules connected in parallel		Total array short circuit current (A)		Safety factor		Rated current of protective device (A)
5	×	*1*	=	*5*	×	**1.25**	=	*6.25*

Controller / Main Load Description								
Total DC load power (W)		Nominal system voltage (A)		Maximum DC load current (A)		Safety factor		Rated current of protective device (A)
48.6	÷	*12*	=	*4.05*	×	**1.25**	=	*5*

Battery Description								
Maximum current of a module (A)		No. of modules connected in parallel		Peak current from PV array		Safety factor		Rated current of protective device (A)
4.72	×	*1*	=	*4.72*	×	**1.25**	=	*3.78*

Inverter Description								
Total AC load power (W)		Nominal system voltage (A)		Power factor (decimal)		Safety factor		Rated current of protective device (A)
-	÷	-	÷	-	×	**1.25**	=	*N/A*

Branch Circuit # 1 (specify)					Branch Circuit # 1 (specify)				
Rated load current (A)		Safety factor		Rated current of protective device (A)	Rated load current (A)		Safety factor		Rated current of protective device (A)
	×	**1.25**	=	*N/A*		×	**1.25**	=	*N/A*
Branch Circuit # 3 (specify)					**Branch Circuit # 4 (specify)**				
Rated load current (A)		Safety factor		Rated current of protective device (A)	Rated load current (A)		Safety factor		Rated current of protective device (A)
	×	**1.25**	=	*N/A*		×	**1.25**	=	*N/A*

Circuit	Protective Device (No. of Devices) CB	Fuse	Switch	Surge	Rated Current (A)	Rated Voltage (V)	Descriptions
Module to controller		*1*			*10*	*250*	*HBC fuse*[1]
Controller to battery			*1*		*10*	*250*	*DPST switch*[2]
Controller to load		*1*			*10*	*250*	*HBC fuse*

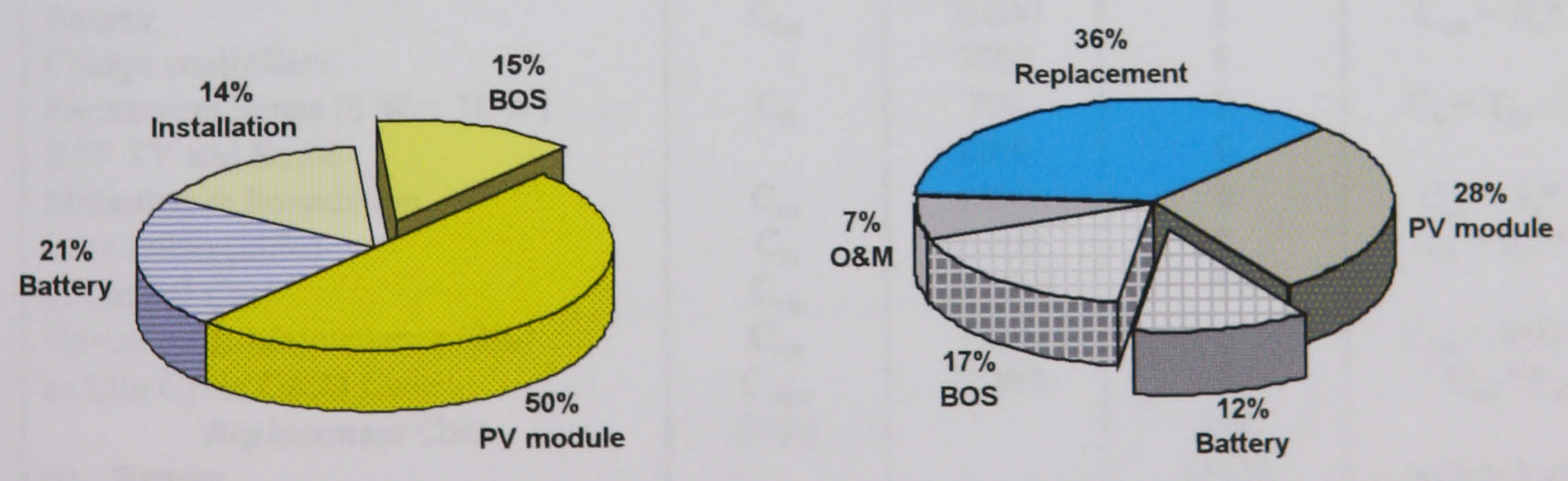
Design Notes:

1) High breaking capacity fuse with fuse-holder 30 A rated.

2) Double pole single throw switch.

DC Wring General Worksheet # DCW	DC Wire Sizing Specification				
Descriptions	System voltage (V)	Maximum current (A)	Allowable voltage drop (%)	Wire size (mm^2)	Wire type
Array Circuit					
Module to Module					
Array to Control Building					
Array to Controller	*12*	*6.25*	*2*	*2.5*	*THW*
DC Circuits					
Battery to Battery					
Battery to Controller	*12*	*5.9*	*2*	*4*	*THHN (battery cable)*
Battery to Inverter or Converter					
Regulator to DC load	*12*	*4.05*	*3*	*2.5*	*THW*
Branch Circuit					
1. *N/A*					
2.					
3.					
4.					
5.					
System Grounding	Wire Size (mm^2)		Wire Type		Type of Earth Ground
Equipment Ground	-		-		-
System	*6*		*bare copper wire*		*to ground rod*
Design Notes:					

5.7.5 Life Cycle Cost Analysis of a Solar Home System



(a) Capital Cost of a Solar Home System

(a) Life Cycle Cost of a Solar Home System

Figure 5.16 Cost elements of a solar home system

Table 5.11 Life cycle cost analysis of a solar home system

Project/Site : Udon Thani, Thailand		**Type of system :** PV solar home system		
1. Financial parameters	*Symbol*	*Values*	*Unit*	*Remark*
Period of analysis	n	20	years	project lifetime
Discount rate	d	0.10		
Inflation rate	i	0.05		
Discount factor	a	0.954		$a = (1+i)/(1+d)$
Annualised factor	$P_{a(n)}$	12.65		$P_{a(n)} = a(1-a^n)/(1-a)$
2. System specification and performance				
Daily load	L_d	13.02	kWh/day	100 households
Annual load	L_a	4752.3	kWh/year	$365*L_d$
Solar Module				
Array size	S_a	8500	W_P	100 households
Module unit price	S_p	6	$/W_P	silicon cells
Lifetime	S_{lt}	20	years	
Battery				
Battery capacity	B_c	144	kWh	100 sets
Battery unit price	B_p	150	$/kWh	
Lifetime	B_{lt}	5	years	
Controller				
Charge controller unit price		7000	$	100 sets
Controller lifetime		5	years	
Power Conditioner				
Inverter size		-	kW	
Inverter unit price		-	$/kW	
Lifetime		-	years	
End-user loads				
Fluorescent lamp 8 W	T_{fl1}	300	$	100 sets
Fluorescent lamp 18 W	T_{fl2}	400	$	100 sets
Lifetime		2	years	
B/W TV and Radio		8000	$	100 sets
Lifetime		10	years	
Mounting and Foundation				
Mounting & Foundation unit price	K_p	0.5	$/W_P	
Lifetime	K_{lt}	20	years	
3. Cost data				
PV array	C_{pv}	51000	$	$C_{pv} = S_a * S_p$
Battery	C_{bat}	21600	$	$C_{bat} = B_c * B_p$
Charge controllers		7000	$	
Fluorescent lamps (8 W + 18 W)	C_{fl}	700	$	$C_{fl} = T_{fl1} + T_{fl2}$
B/W TV and Radio		8000	$	
Mounting & Foundation	C_{sw}	4250	$	$C_{sw} = S_a * K_p$
Installation (20%)	C_{in}	10200	$	$C_{in} = 0.2*C_{pv}$
a) Capital Cost	C_{cap}	**102750**	$	
Operation & Maintenance (2%)	C_{om}	1020	$	$C_{om} = 0.02*C_{pv}$
b) Life Cycle O&M Cost	$C_{o\&m}$	**12903**	$	$C_{om} * P_{a(n)}$
Replacement Cost	*Yr.(i)*		*PW*	
(i) Battery			41472	every 5 years
(ii) Charge controller			13440	every 5 years
(iii) Fluorescent lamp (8 W + 18 W)			4340	every 2 years
(iv) B/W TV and Radio			5040	every 10 years
c) Life Cycle Replacement Cost	C_{rep}		**64292**	
d) Salvage	C_{sal}		**-0.0**	
4. Economic indicator				
Total Life Cycle Cost	LCC	**179945 US$**		LCC = a+b+c+d
Annualised LCC	ALCC	**14224.90 US$/year**		ALCC = LCC/$P_{a(n)}$
Cost of Electricity	COE	**2.99 US$/kWh**		COE = ALCC/L_a

5.8 Comparison of PV System Sizing and Costing of Different Types

According to the specific design of PV systems of different types are described in previous topics above, the results can be compared with regard to sizing and life cycle cost. They are considered in the following tables.

Table 5.12 PV system sizing of different types based on the same load conditions in Table 4.3 in the sample village with 100 households

System Types	Array Size (kW_P)	No. of Modules	No. of Batteries
Battery Charging Station	10.62	125	100
Pumping System	1.13	12	-
Refrigeration System	0.68	8	6
Public Lighting	2.80	40	20
Community Facilities System	1.61	19	18
Solar Home System	8.50	100	100

Table 5.13 Comparison of LCC analysis for economic indicators of different system types in $US (based on 100 households)

System Types	Capital Cost ($)	Levelised Energy Cost ($/kWh)
Centralised Mini-Grid System	263,470	2.89
Battery Charging Station	108,860	8.54
Pumping System	13,670	1.24
Refrigeration System	8,110	3.38
Public Lighting	31,460	3.37
Community Facilities System	17,570	2.54
Solar Home System	102,750	2.99

An optional design of PV systems for a Thai rural village can be considered from the results of these designs. As can be seen from the Tables 5.12 and 5.13, the solar home system is the least-cost option compared with the centralised PV mini-grid system and the battery charging station system based on the same load conditions and the same village facilities with 100 households in the sample village. The capital cost of the LCC analysis of the centralised PV mini-grid system is high because the costs of an auxiliary source and the power conditioner, for example a diesel generator and an inverter respectively, are included as well as the cost of installation of a mini-grid system (distribution low voltage line system). High installation costs and high maintenance costs of the back up diesel generator are also considered. In contrast, other PV systems in Table 5.13 are stand alone with DC loads, the additional cost of these equipment or parameters mentioned above are not considered. Accordingly, the capital cost or the investment cost of a stand alone PV system can be lower compared with a centralised PV mini-grid system.

5.9 Summary

This chapter presents analytically specific design for stand-alone PV systems in the sample village at Udon Thani province of Thailand. These are decentralised PV systems, the design is based on the same load conditions in Table 4.3 for the design of a centralised mini-grid system. It also presents a system sizing method that can be completed without access to a computer programme. The results of the sizing methods presented have been cross-checked against a computer programme, the results are consistent. Instructions and blank worksheets are provided in appendix E. Although they are designed for application in Thailand, they could be applicable anywhere with a similar climate and latitude angle.

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Chapter 6

Proposal of a Strategic Model for PV Dissemination (Case Study in Thailand)

Chapter 6

6.1 Introduction

The process of information dissemination is necessary for the successful implementation of PV programmes in developing countries, and it is essential to consider the strategies for implementation of a PV project to ensure that it will be successful. This chapter proposes a strategic model for PV dissemination and discusses the roles of key players in the implementation of the strategy and the responsibilities of these organisations.

6.2 Institutional Aspects

Both international and national institutions have an essential role to play in the dissemination of PV in the rural areas of developing countries. The roles of these institutions can be described as follows:

6.2.1 Role of the National Government

Most national governments in developing countries give high priority for rural electrification to meet social and regional development and economic goals and to increase the standard of living and the quality of life of people in the rural areas. In many situations, a PV system is the most cost-effective means of providing electricity for small loads in remote areas in the short term. Its modular nature also means that the funds allocated produce visible results quickly, rather than having to wait for the completion of utility grid extension after many years. The key roles of the government can include [1]:

(i) Collaboration : The government must work with national or international lending institutions to establish the credit channels necessary to provide rural households with the initial capital needed to buy the PV system. In many countries, it is not possible to establish these channels without government backing.

(ii) National policy : The government must be concerned with the macro-economic policies needed to bring progress to the country and promote the well-being of the people. The macro-economic benefits of rural electrification are very clear, although the micro-economic concerns of individual Ministries do not always reflect this. In particular, policies intended to assist rural areas through subsidies on say kerosene, can hinder the expansion of PV. The Government needs to consider all of the factors which promote or hinder rural development and introduce national level policy changes which optimise this development, and address PV policy and planning, funding and financing, technology research and development.

(iii) *PV centre* : The government can facilitate the installation of good quality system by funding a National PV Centre. A centre must have the technical resources sufficient to undertake PV activities, such as R&D, information collection and dissemination, consultancy, testing and training programmes including setting standards for PV suppliers and taking measures to ensure that they are observed. National standards normally should be based on accepted international standards.

(iv) Duty and tax structure : The Government plays an important role in facilitating the import of the PV system, and can also facilitate appropriate economic and political climates to attract international investment in the production of PV technology [2-5]. Where some PV components need to be imported, the tax on these goods should be kept as low as possible, so as not to disadvantage local system suppliers. The Government must also ensure that there is a "level playing field" for all of the technologies, without a distorting tax or subsidy which could force users into micro-economic decisions which are at variance with the Government's macro-economic policies.

(v) Encourage : The government must encourage the private sector and stimulate small local industries into a step by step development of the technology. The government can also promote public awareness of the environmental and other benefits of PV technologies.

(vi) *Funding and dissemination* : Some PV projects attend to the social needs of communities rather than the private needs of individuals. Such projects as the provision of clean water, power for schools and medical or community centres are a Government responsibility in rural areas, just as they are in urban areas, and should be funded on the same basis. Because of the large macro-economic benefits of rural electrification, and the cost-effectiveness of PV in this context, it is to the benefit of the Government to promote the use of PV by individuals for their private use. The establishment of demonstration projects, to familiarize people with the use and the benefits of PV technology, is a valid use of public funds, and these should be part of any information dissemination campaign to the general public.

6.2.2 Role of Donor Agencies

International donor agencies have an important role to play as sources for PV project funding and often as sources of expertise. The World Bank group [6,7], which includes the International Development Association (IDA), the Multilateral Investment Guarantee Agency (MIGA), the International Finance Corporation (IFC), and the International Bank for Reconstruction and Development (IBRD) has provided funding for PV projects for many years. Within the World Bank there are areas particularly concerned with PV such as the Asia Alternative Energy Unit (ASTAE) and the Financing Energy Service for Small Scale Energy User (FINESSE) unit which have great experience in PV applications and in "best practice" in designing PV projects. The United Nations, particularly the UNDP and UNIDO, and other multilateral lending institutions have provided support for PV projects in many countries. Following the Rio summit, the World Bank set up the Global Environment Facility (GEF) to fund and promote clean technologies. One of its mechanisms is the PV Market Transformation Initiative (PVMTI) which is seeking to promote private sector investment in PV by providing concessionary finance for projects in countries where the PV market is close to commercial take-off. Many other agencies have also played key roles in promoting PV in developing countries. The European Union has provided considerable funding for PV, and promoted technology transfer and training in many countries. The USAID of the USA, GTZ of Germany and NEDO of Japan have also been very active in installing demonstration systems and in training of local personnel. All of these agencies play an important part in knowledge and technology transfer, through the dissemination of information on PV technologies, proper design, system management, planning and training. They also encourage the expansion of PV projects through the private sector and Non Government Organisations (NGOs).

6.2.3 Role of the Electric Utilities

The utilities are the most appropriate bodies to develop a code of practice for the installation of PV technologies appropriate for power generation, while the government should coordinate the effect. They can be a partner in schemes to bring PV systems to non-electrified areas, and can also provide training courses for local installers, technicians and end-users [8]. Quality control and reliability can be maintained through the technical expertise available within the electric utilities, as in the Mexican PRONOSOL programme. The electric utilities in Thailand have been involved with PV programmes for many years. EGAT introduced PV into its renewable energy programme in the late 1970s and has been active ever since, and the Provincial Electricity Authority has also installed PV power plants.

6.2.4 Role of Educational/Research Institutions

They are the most appropriate organisations to carry out, i) Research and development (where the expertise and resources exist), ii) Co-operation in international, national, regional programmes in collaboration with the government and private sector, iii) Training of engineers, technicians and end-users, iv) PV dissemination campaigns, v) Provision of PV workshop and seminars for both national and international audiences, vi) Demonstration of the PV systems in applications with educational technologies.

6.2.5 Role of the Private Sector and NGOs

The private sector must eventually become the dominant force in PV, just as it is in the supply of candles, bicycles, and all the other products which people use. At the present time the PV industry worldwide is small, and unable to finance all of the cost of developing the supply and maintenance networks needed to bring PV to the rural populations of developing countries. The standard route to the growth of the PV market in these areas would be to ignore the rural poor until the rich urban market in the industrial countries had grown to a size which could support the investments needed. This would, however, leave the rural poor without hope of improved quality of life for many years and this is usually regarded as being politically unacceptable. Such a policy would also re-enforce the dominance of the large multinational companies and severely disadvantage indigenous companies. To help overcome these problems, most Governments in developing countries seek to bring the private sector into their PV programmes as a means of encouraging the growth of their experience and expertise and giving them a basis for their financial growth.

Private companies in developing countries can gain a foothold in the PV market through installation and maintenance of systems as part of a Government or international PV project. The next step would be to begin to help in the design of systems for local conditions, and later to begin local manufacture of BOS components. Those countries with an engineering capability could eventually manufacture all the components of a system. However, it is probably unwise for the large majority of countries to contemplate the manufacture of solar cells because their cost is so dependent on the scale of manufacture that only a few companies worldwide will remain in the business over the next 10 years.

The role of the private sector in a country such as Thailand is in the local installation and maintenance of PV systems, the manufacture of some BOS components and the production of PV systems from local and imported components. They can also take responsibility for the demonstration of PV systems and training in rural areas in partnership with the government and/or international agencies. NGOs usually work closely with local communities and are trusted to give impartial information. They can thus be very important in disseminating information and promoting technology acquisition to grassroots communities. They can take action as a local partner with other organisations for rural PV programmes, whilst a few NGOs (those with international outreach) are providing financing and facilitating the flow of capital from the international market to local users.

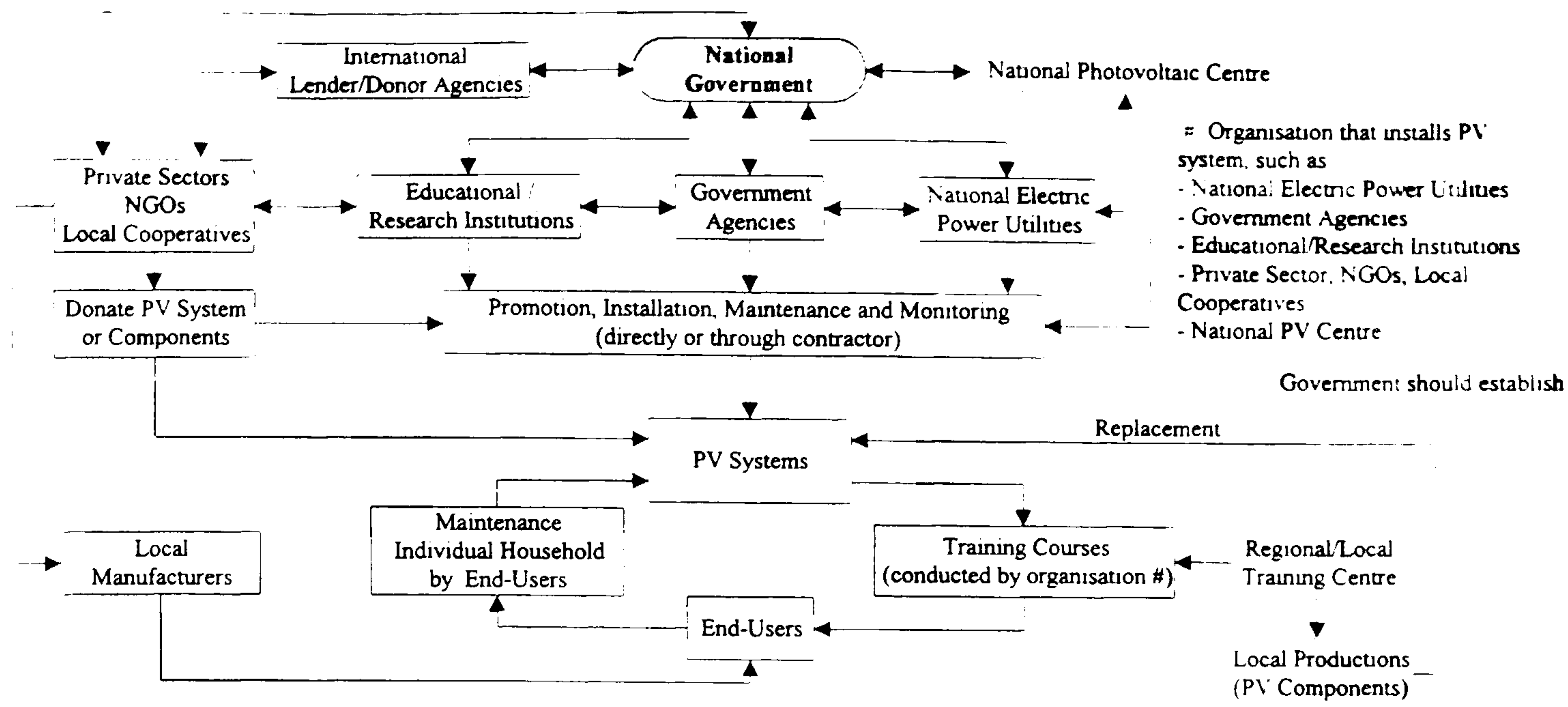

Figure 6.1 Proposal of a strategic model for PV dissemination.

6.3 Implementation Scheme and Strategy

The key players in the implementation of the strategy are international donor agencies, the government (agencies), the electric utilities, educational/research institutions, private sector and NGOs. These institutions must work hand in hand with the full participation of the rural communities for the successful dissemination of PV in developing countries. Figure 6.1 shows a strategic model for PV dissemination. This model, as a case study for Thailand, is discussed in the following.

The promotion of PV in Thailand has been successful, with a total installed capacity of about 7 MW_P so far, but the rate of capacity growth from 1971 until today has been quite low. The lack of any financing mechanism is one of the most important reasons for this slow development, particularly since there has been an emphasis on central battery charging systems rather than on small solar home systems. In general, previous PV projects needed to be funded by Government agencies. For future, larger scale projects it would be more appropriate to seek funding by international donor agencies who have the potential to help in the development of sector programmes and projects, assist in financing, give technical assistance and training and carry out post project appraisals. The role of the World Bank should be strongly promoted in Thailand for PV programmes, just as in Indonesia, where the World Bank, through the Global Environmental Facility (GEF), are planning to assist the Indonesian

Government in providing Solar Home Systems (SHS) in about 200,000 households. The Indonesian Government, before the financial crisis, had plans for 1 million households, 50 MW_P, by 2005 [9]. Most PV projects in Thailand were funded by the Government through its agencies and/or the electric utilities (with technical assistance by international organisations in some projects). To gain increased support from international donor organisations, the Government needs to set a target for installed PV, as part of a long-term plan of action for rural infrastructure development. There needs to be a careful consideration as to whether the programme should promote central battery charging stations or the Solar Home Systems which are such a proven success in most other countries. Once the programme is decided, the Government can then approach the GEF or other such organisations for funding and technical assistance.

6.3.1 Institutional Approaches for the Introduction of PV Systems to End-Users

The strategy of promoting PV system through institutions to local communities must be implemented in a number of different ways, depending on the degree of penetration of PV systems into an area. When PV is first introduced into an area, the funding and the personnel must come from outside the area, usually from Government and its agencies, in the form of demonstration projects. Local companies and individuals can be trained in installation and maintenance during these projects, and the users can be given training in the operation of the PV systems and realistic expectations of their performance. Expansion of the PV programme can build on this experience to set up local companies to install and maintain systems designed and funded by central Government or international agencies. It is essential that the users are charged a fair price for their PV systems during these early stages, so that the dissemination projects can lead into a situation where systems are supplied and all costs are recovered on a commercial basis. The local companies can establish relations with a central supplier of systems and components, and with a source of finance. They can then begin to sell PV systems in their area on a commercial basis. At this stage, the role of Government is to act as a regulator of quality, to provide equality of taxes/subsidies for equivalent products and services and to facilitate the provision of finance at reasonable interest rates, either from indigenous or international sources. The Government should also ensure that the educational system provides the output of trained people required by the PV programme at the various levels.

6.3.2 PV Market Development

As discussed earlier, the national economy benefits greatly from the widespread use of PV systems in rural areas, and it is therefore very much in the interest of Government to increase and encourage the PV market. The Government should act in the first instance to remove barriers to market expansion, by removing excessive duties and taxes on PV components and systems, removing subsidies on products which compete with PV systems, such as kerosene. They should also provide information on the benefits and costs of PV to the public, to Government agencies and power utilities and to financial institutions.

The Government may choose to go beyond the removal of discrimination against PV and decide actively to promote its use. It can reduce the cost of PV systems by reducing or even abolishing import duties and taxes on PV systems or components. The Government could introduce new regulations for the promotion of PV systems through tax reduction for investments in PV by private industry or individuals [10]. Government Departments should always include PV as an option for powering schools, medical centres, community centres, street lighting etc., and should be used wherever it is cost-effective on a life-cycle basis.

The Government should support efforts to develop innovative financing mechanisms which allow lenders to offer long term credit on reasonable terms. This may be through commercial banks via risk-reduction guarantees, through Rural Development Agencies or Credit Unions, or by on-lending of low-cost international credit from mechanisms such as the GEF.

The Government should introduce policies to help NGOs and local cooperatives to participate in PV dissemination by offering them training in business practice as well as in PV technology, providing a transfer of up-to-date information and best-practice through workshops and seminars. It is essential that the Government encourages local industry and contractors to became involved in the PV industry. The indigenous production and promotion of PV technologies are essential elements in the sustainability of the widespread application of PV, giving minimum cost and maximum benefit to the local economy, provided that the quality of performance is maintained at international standards.

6.3.3 Training

Training is essential at all technical and business levels. The Universities and research institutions should provide professional training with courses, seminars or workshops on all aspects of PV science and technology. The technical colleges and the electric utilities should also provide training in technical practices for installation and maintenance. The government, with PV industry support, should set up specialist regional/local training centres. Although in the early years of PV dissemination, lower level training activities can be carried out by itinerant staff as and when needed in a local school or technical collage, in the later years technical training will be required at many different levels, and it is most effective if the expertise and facilities are concentrated in a small number of centres. These centres could, in particular, provide the training for those who provide the low-level local training of installation and maintenance technicians. Training in business practices is essential if the local companies are to be successful, and training of financial staff is critical to the success of a funding agency. Training costs for specific projects may be as high as 24% of total cost, through they tend to average around 5% [11,12]. Training needs and costs will be highest during commencement of operations and during phases of expansion, but the investment in well-trained staff is very cost effective. The government should provide and support training activities in collaboration with private sector PV providers, since the existence of these trained personnel is essential if PV is to develop as an indigenous business.

6.3.4 Assessment and Feedback

All PV projects should be evaluated after they have been operational for a year and for the whole life of the system. The feedback from these studies is essential to determine the best-practice in design and installation, and to obtain the opinions of the users. It would also help the Government to refine national policies on PV dissemination in Thailand. The electric utilities should have a quality control system, which not only checks the suitability of the PV systems on offer, but should visit each village to check on the system performance and to obtain feedback on the satisfaction of the villagers [13]. The results must be fed back to a central agency, responsible to the Government, since lessons learned from each region could be even more valuable if they are compared at national level. The assessment can be conducted by any independent body, either a local company, the electric utilities and NGO or some international organisations.

6.4 Solar Home System Projects

There are about 265,000 households (in 1998) in rural areas of Thailand for which there is no plan for electrification because of remoteness or inaccessibility. On a life cycle cost basis, PV lighting has been shown to be cheaper than that from a kerosene or hurricane lamp[14]. Solar home systems are economically the least-cost option, compared with kerosene mantle and wick lamp for lighting and rechargeable batteries used for operating small appliances such as TV and radio. The SHS is now the most common PV application in many developing countries. Based on the analysis of existing projects in rural areas of Thailand, SHSs should be much more encouraged.

6..4.1 Implementation

Typically, it is national governments which launch the SHS programmes as part of rural development schemes. In many countries, the electric utilities are responsible for technical aspects and quality control of PV electrification, sometimes with a technical assistance programme from international organisations. For countries which are beyond the stage of small demonstration projects, local private companies are contracted to install the systems and provide the training of the users. Local government agencies and NGOs are used to disseminate information, and, in areas of extreme poverty, the end-users can pay some or all of their contribution to capital costs by participation in construction and maintenance. Research institutions can also cooperate with system monitoring and an assessment of both technical performance and social issues arising from the introduction of PV.

6.4.2 Financing

The capital cost of a system depends on many factors, apart from the international prices charged to the importer. These include duties and taxes imposed by the Government, the costs of wholesale and retail distribution, and the cost of installation. The price paid by the customer also depends on the cost of finance, and will vary depending on interest rates and on how long the customer takes to repay the loan. The possible down payment by the customer depends on their income stream, and on the policies of the central Government. Ideally, the repayment period should be short since the total interest charged will increase if the repayment period increases. To increase the number of households able to pay for SHS, the repayment strategy should be flexible, and in some countries is designed to enable payment when produce is sold at market. Where financing is organized through local co-operatives such as farmers' unions, it is possible to make payments in produce rather than cash. Based on successful SHS projects in some countries, typical finance terms on basic PV systems (lighting, TV and radio) are shown in Table 6.1.

Table 6.1 Typical finance terms of SHS projects in some countries [4,7,9].

	System cost (US$)	Down payment (%)	Repayment (yrs.)	Interest rate (%)
Indonesia	400	35	10	0
Sri Lanka	300	10	5	10
Dominican Republic	500	10	5	15

The SHS projects have often been implemented with co-financing by, for example, the World Bank, ASTAE or the Asian Development Bank, with some repayment from end-users and suppliers, and the balance of the total cost being met by the government. However, in countries where the cash income is very low, donor agencies and energy planners must find a balance between the users' ability to pay and the programme goals. If the PV programme is to be sustainable then the users must pay at least the cost of maintenance and battery replacements. This can be ensured by setting up a fund into which end-users pay a small monthly charge, for example, US$ 1.5/month. In most countries, it has been found that rural people are paying about US$10/month for kerosene and batteries. This is usually sufficient to make the monthly payment needed to purchase a basic SHS over about 5 years on a purely commercial basis. Provided that a supply and distribution network is in place from previous PV projects, the supply of SHS can become a normal business activity. The PVMTI programme, described earlier, is currently operating to establish just such a business activity in selected countries, and provide examples to other countries whose PV markets are similarly advanced. The development of international quality standards for PV systems and components, such as the Global Approval Program, is essential for the success of such developments. Companies must offer high quality PV products because if the systems do not function well, the end-users will become dissatisfied and refuse to make the monthly payment or even return their PV system.

The SHS programmes in other countries provide valuable lessons for Thailand in considering policies for the future of PV. It seems clear that SHS provide a suitable level of service for households in rural areas at a monthly cost which is comparable to their present monthly outlay on lighting and small power. This contrasts with the situation for battery charging stations where the capital cost is beyond the capabilities of almost all individuals or local companies.

6.5 Summary

Since 1976, PV systems in Thailand have been increasingly used to solve rural electrification problems in response to the policy of the government for rural development. At present, there are approximately 7 MW_P of PV systems installed in various rural areas across the country. There is a target to install up to 20 MW_P [15] between the 8th National Social and Economic Development Plan (1997 and 2001) and the 9^{th} National Social and Economic Development Plan (2002-2006). In order to meet this target it is important to devise strategies for proper implementation and a model for PV dissemination in Thailand. It is also essential that the policy makers consider the lessons from other countries in choosing the type of PV system to be installed. Aid programmes, whether by national Government or international agencies, can not afford to reach more than a tiny fraction of the population who need PV. It will become available to the majority of those who need it only if PV becomes a normal commercial business and PV systems are bought by customers on a commercial basis, in the same way as radios or bicycles. Central PV systems are not an appropriate basis for a commercial market, whilst SHS have already been proven, in some countries, to be commercially viable. It seems sensible therefore to move towards a commercial market for SHS with Government provision of PV systems for public services in health, education and communal buildings.

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Chapter 7

7.1 Conclusions

The major work in this research programme was the design and analytical evaluation of stand-alone PV power systems for rural areas in Thailand. A sample village with 100 households at Udon Thani province of Thailand was selected for the design of PV systems. Both a centralised PV mini-grid system and a decentralised PV system for specific end-users were designed. The computer programmes were specifically developed for this study because the process of systematic analysis in some topics is complicated.

Consideration of the design of a centralised PV mini-grid system in the sample village in Thailand discussed in chapter 4 has shown that the design of this system type is more complicated since there is much useful information needed. A computer programme was developed to calculated the daily state of charge of the battery throughout the year. The inputs to the computer programme include array and battery size, load profile, the I-V characteristic of the solar module and daily global solar radiation on an inclined surface at the design location in Thailand (which was analysed by a computer programme described in chapter 3). The conductor size and type of a mini-grid system in the sample village were calculated and the design also considered the cost-effectiveness of different levels of protection and risks associated with a lightning strike. The design of decentralised PV systems, such as the solar home system, battery charging station, water pumping and public lighting in the sample village in Thailand, based on the same load conditions and the same village facilities as discussed in chapter 5, was less complicated than a centralised PV mini-grid system. These PV systems were designed without the need for a computer programme.

There are three main types of PV applications which can be installed in a Thai rural village based on the same load conditions and the same village facilities. A centralised

PV mini-grid system, a battery charging station and a solar home system were designed for this study. To design a battery charging station, the array size depends mainly on the number of charging points (units), ampere-hour loads that need to be charged and local solar radiation. Considering all DC loads (100 households) in the sample village in Thailand, a battery charging station provides electrical power for charging the batteries used in each household. Other loads, such as public lighting, water pumping, refrigeration/freezer, and community facilities were designed as PV individual systems. For the solar home system, a typical load for this system is lighting. By reducing the amount of power used for lighting, the householder can also use a small black and white television. Other loads for the village facilities were also designed as PV individual systems.

Three main PV systems, namely a centralised mini-grid system, a battery charging station and a solar home system, can be compared in terms of possible benefits and problems for using each PV system type in a typical Thai rural village.

- **Centralised Mini-Grid System**

When the public loads and community facilities are considered to operate under the control of a single system, a centralised mini-grid can be designed to cater for the overall village energy needs. It is usually designed to provide 220 VAC which feeds the village distribution grid. The power station consists of a large PV array, a control room housing the electronic load controllers, a large inverter and switching gears, battery storage and a back up diesel generator. Experiences from other countries have shown that, shortly after a centralised mini-grid was installed in a village on an energy need basis, the demand greatly exceeds installed capacity. This is because extra unauthorised loads, such as TV sets, and other electrical appliances are used. Another problem is that the equipment is very sophisticated and repair and maintenance are also costly. The investment cost of a centralised mini-grid system is extremely high. Even though it closely mimics a conventional electrification system, it is much more restricted in the loads. Seemingly, interest in the centralised mini-grid systems has been declining in the light of the experience gained to date.

- **Battery Charging Station System**

A fairly sophisticated load control system is required to regulate the charging of each of the batteries. An over-discharge protector should be installed in each household to protect the battery from over-discharging. In addition, all users or battery owners have to transport their batteries to the station and pick them up after the batteries are fully charged. This process may involve expenditure of time and money. One of the big problems is that system failures cannot be technically repaired by a skilled person in the village. The waiting time for repair is long and this causes disillusionment amongst the villagers and a reluctance to use the PV station. Since skilled manpower is so scarce in remote areas, any systems having other than very simple operating or maintenance requirements are generally unsuccessful. The local small population, especially hill-tribe people, cannot provide skilled manpower and cannot usually keep those who may have been trained as part of a PV project. The system costs or sizing will vary greatly depending on local solar radiation and the number of charging points (units), which should be sufficient to avoid long queues.

- **Solar Home System**

The advantages of a SHS are associated not only with improved lighting, but also with the elimination of dry batteries for radio/tape cassettes (whose cost usually represents a significant part of the annual earnings of an average rural family), and with the possibility of access to a television. Users can also work at night, adding income for their families, and children can have quality of studying, but the system sizing will be larger as well. Furthermore, a SHS usually requires DC appliances that have not been widely available in some rural shops, especially in Thailand, and are more costly than AC appliances. The investment cost of a SHS is too high for a rural family to pay as one single payment, but this problem can be overcome through appropriate financing schemes.

The appropriate method of the life cycle cost analysis was used for comparing different electrification options. The life cycle cost analysis was based on the key assumptions used in estimating the cost in the year 2000 (see Table 4.19). The costs of installation and operation and maintenance were estimated by multiplying the capital cost of the PV arrays by 0.2 (20%) and 0.02 (2%) respectively. As a result, the present worth of different PV systems was compared and the least cost option selected. The results of this study for comparison of capital cost of different PV system types and life cycle costs can be concluded as follows:

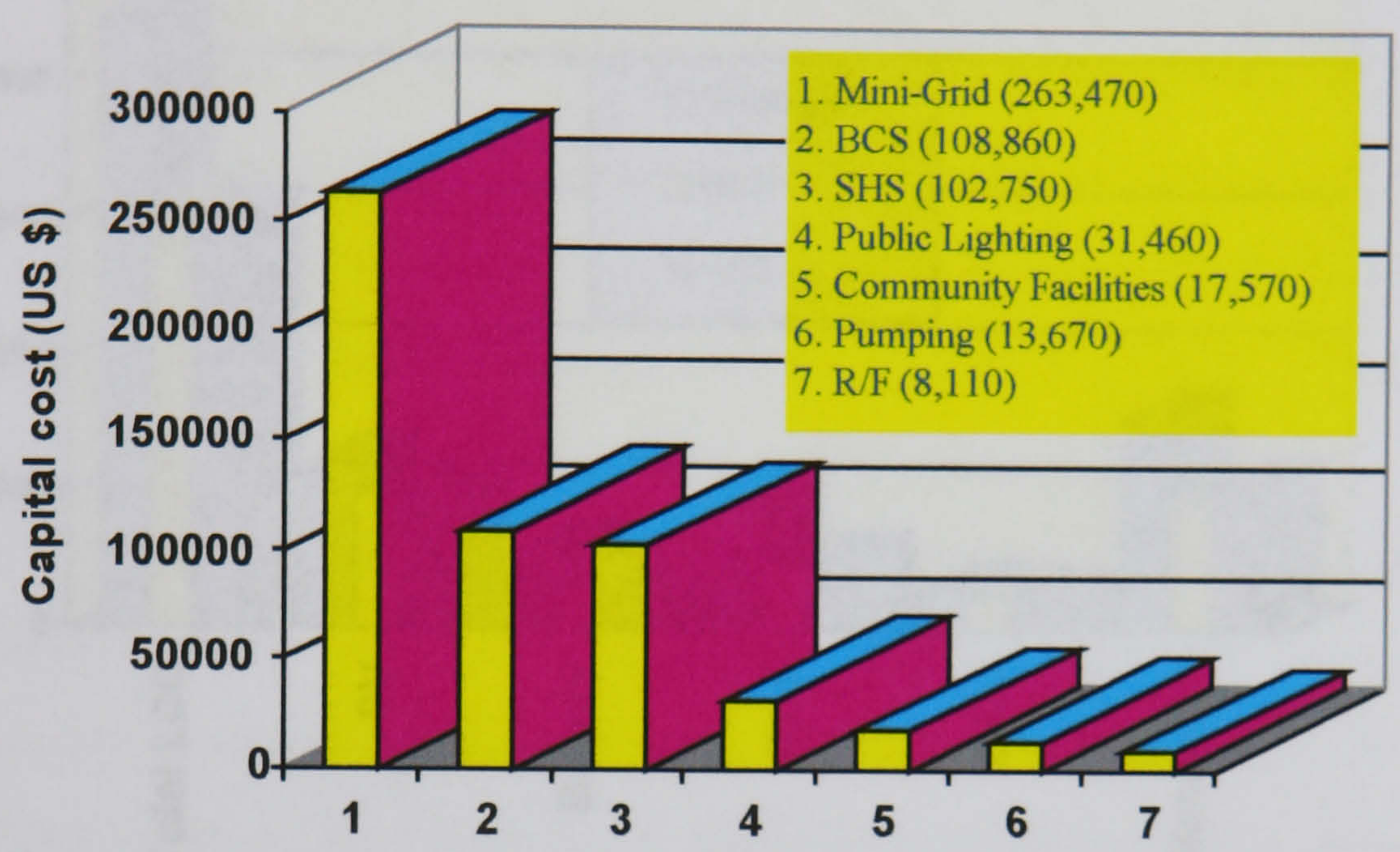


Figure 7.1 Comparison of capital cost in US$ of different PV system types (based on 100 households in the sample village in Thailand)

Table 7.1 Comparison of life cycle cost (LCC) of 3 different PV systems in US$ (all loads are included) for PV mini-grid system, battery charging system (BCS) and solar home system (SHS) based on 100 households in the sample village in Thailand.

System Types	Total LCC (%)	PV (%)	Battery (%)	BOS (%)	O&M (%)	Replacement (%)
Mini-Grid	450,530 (100)	122,400 (27.2)	57,600 (12.8)	83,471 (18.5)	30,967 (6.9)	156,092 (34.6)
BCS	307,110 (100)	101,100 (32.9)	34,092 (11.1)	49,490 (16.7)	25,579 (8.4)	96,849 (31.5)
SHS	302,850 (100)	88,350 (29.2)	34,092 (11.3)	51,127 (16.9)	22,352 (7.3)	106,929 (35.3)

The capital cost shown in Figure 7.1 is the initial cost of the system when the project is implemented. As can be seen from the figure, a SHS is the least-cost option when compared with a centralised PV mini-grid system and a PV battery charging station based on the same load conditions and the same village facilities (100 households) in the sample village in Thailand.

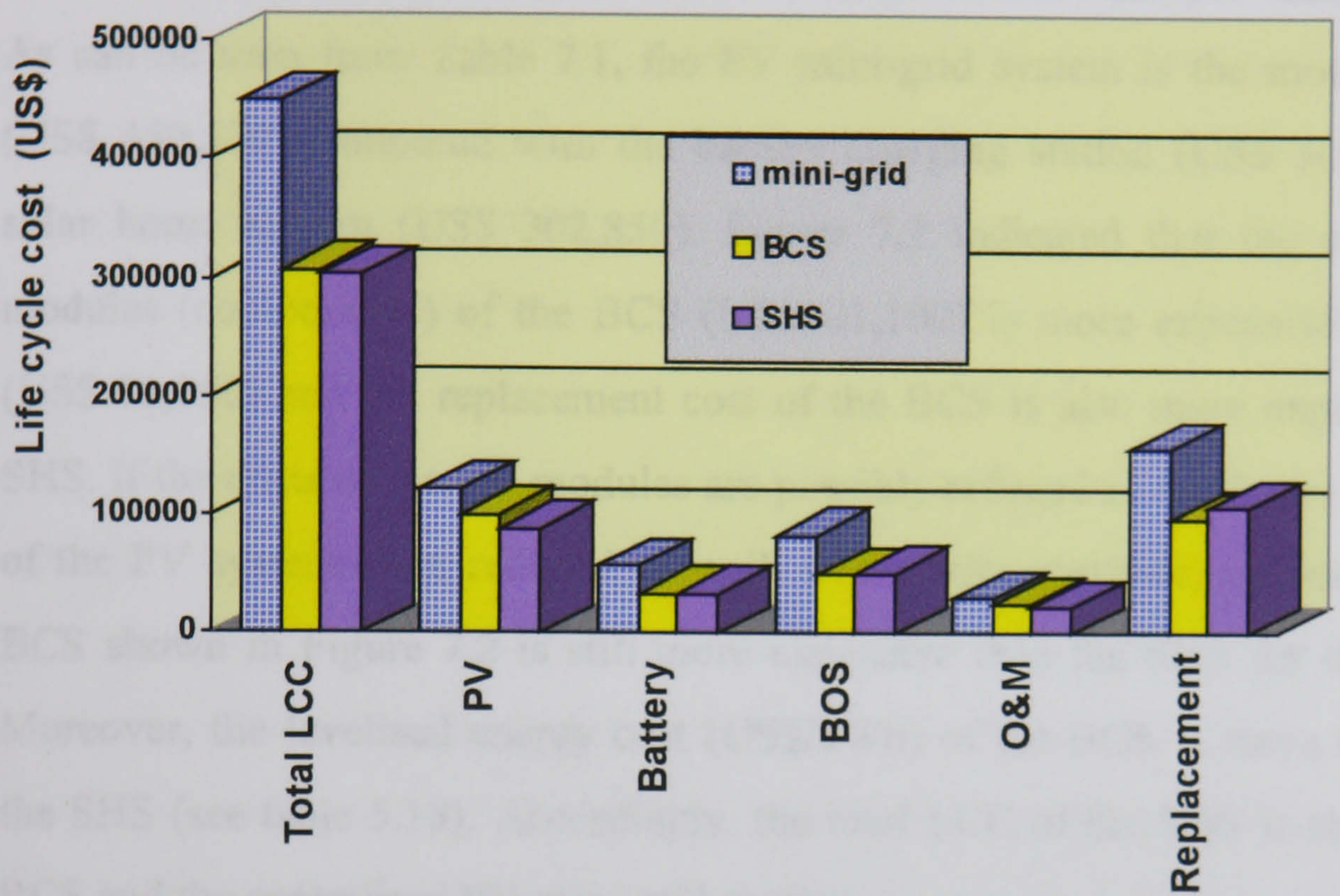


Figure 7.2 Comparison of life cycle cost in US$ of 3 different PV system types for SHS, BCS and mini-grid system based on 100 households in the sample village in Thailand

The investment cost of a centralised PV mini-grid system is high because the costs of an auxiliary source and the power conditioner, for example a diesel generator and an inverter respectively, are included as well as the cost of installation of a mini-grid system. High installation costs and high maintenance costs of the back up diesel generator are also considered. In contrast, other PV systems in Figure 7.1 are stand alone with DC loads and the additional cost of these equipment or parameters mentioned above are not considered. As a result, the capital cost of a stand alone PV system can be lower compared with a centralised PV mini-grid system.

The life cycle cost (LCC) analysis of each PV system type was estimated in the previous chapter but this study focuses on 3 main types of PV applications which can be installed in a typical rural village based on the same load conditions and the same village facilities. A centralised PV mini-grid system, a battery charging station and solar home system was determined in this case. The LCC analysis gives an economic indicator of a system and calculates the total expected costs over the lifetime of the system. Table 7.1 shows comparison of LCC of 3 PV different systems in US$ (all loads are included) for a PV mini-grid system, a battery charging system (BCS) and a solar home system (SHS) based on 100 households in the sample village in Thailand. As can be seen from Table 7.1, the PV mini-grid system is the most costly option (US$ 450,530) compared with the battery charging station (US$ 307,110) and the solar home system (US$ 302,850). Figure 7.2 indicated that the cost of the PV modules (components) of the BCS (US$101,100) is more expensive than the SHS (US$ 88,350) and the replacement cost of the BCS is also more expensive than the SHS. If the costs of the PV modules are possibly reduced in the future, the total LCC of the PV systems will reduced as well. In this circumstance, the total LCC of the BCS shown in Figure 7.2 is still more expensive than the SHS for this case study. Moreover, the levelised energy cost (US$/kWh) of the BCS is more expensive than the SHS (see table 5.13). Accordingly, the total LCC of the SHS is cheaper than the BCS and the centralised PV mini-grid system.

It is clear that a developing country such as Thailand has to use decentralised PV systems rather than a centralised mini-grid system in a typical rural village. This research programme indicates that SHSs provide a suitable level of service for households in rural areas at a monthly cost which is comparable to their present monthly outlay on lighting and small power. This contrasts with the situation for the battery charging station or a mini-grid system where the capital cost is beyond the capabilities of almost all individuals or local companies.

According to this research programme, a SHS is the least-cost option compared with the battery charging station and kerosene mantle and wick lamps for lighting and rechargeable batteries used for operating small applications. It is necessary to consider a strategic model for PV dissemination in Thailand. Central PV systems are not an appropriate basis for a commercial market while individual PV systems such as SHS have already been proven to be commercially viable in some countries. It seems sensible therefore to move towards a commercial market for SHS with government provision on PV systems for public services in health and education.

In general, household PV systems are the least-cost option for a village with fewer than 200 connections and the PV mini-grid system is the least-cost option with 400 household connections and 100 households per km^2 [see reference 4 on page 264]. Based on the analysis of existing projects in rural areas of Thailand, the SHS should be encouraged more strongly. The SHS programmes in other countries provide valuable lessons for Thailand in considering policies for the future of PV.

The strategic model for PV dissemination in Thailand shown in chapter 6 is appropriate and is the only possible one for a country, such as Thailand, which is in the early stages of PV dissemination. It must be clearly recognised by policy makers and all of the other actors that their roles will change over time, as PV becomes established as a rural power source, and that the ultimate aim is for the role of Government and its agencies to be regulators of quality and performance, while local companies and institutions take on the tasks of design, procurement and supply, installation and maintenance, and marketing and finance. This can ensure a smooth transition from demonstration stages to the mature stage of commercial provision of PV systems to the majority of the rural population.

The promotion of PV systems in Thailand has been successful, with about 7 MW_P so far, but the rate of capacity growth from 1971 until today has been quite low. The current plan for PV systems in Thailand has been set for a target of installation up to 20 MW_P from now until the end of the 9th National Social and Economic Development Plan (2002-2006). The target can be met before the end of the plan if the key players in the implementation of the strategy, for example international donor agencies, the Thai government and its agencies, the electric utilities, educational/research institutes, the private sector and NGOs, work hand in hand with the full activity of the rural communities for the successful dissemination of PV (see chapter 6 for the roles of these key players in the implementation of the strategy and the responsibilities of these organizations). The lack of any financing mechanism is one of the most important reasons for the slow development of PV in Thailand, particularly since there has been an emphasis on the central battery charging systems rather than on small solar home systems. In the past, previous PV projects needed to be funded by the Thai government agencies. For the future, larger scale projects, it would be more appropriate to seek funding by international donor agencies who have the potential to help in the development of sector programmes and projects, assist in financing, give technical assistance and carry out post project appraisals. The role of the World Bank should be strongly promoted in Thailand for PV programmes. To gain increased support from international donor organizations, the Thai government needs to set a long-term plan of action for rural infrastructure development. This needs to be a careful consideration of how the solar home systems should be implemented. The Thai government can then approach the international organization for funding. The future development and promotion of PV technology in Thailand should take the following items into consideration as follows:

- In order to set and maintain standards for PV modules and components, a National Centre of technical expertise should be set up, which can act as the conduit between policy formation and the end-user. The centre needs to be aware of the developments in photovoltaics around the world and able to select appropriate products and technical developments for application in rural areas.
- PV is unique in its ability to facilitate desirable social, economic and environmental improvements in the country, especially in the remote areas. It should be considered by all Government Departments when formulating plans for rural development, and used wherever it is cost-effective.
- It is essential to ensure that the PV systems installed provide a service which the users require at a price which they can afford, and that the Government programme is designed in such a way that it will lead naturally to an expansion through the development of businesses selling PV to customers on a commercial basis. The programme must thus promote the establishment of supply networks throughout the country and of local companies to provide maintenance and repair services in rural areas. The indigenous manufacture of PV components or systems to international quality standards should be encouraged wherever this is cost-effective.

The Thai government still has a role to play in PV market development. The government can best support the development of the SHS by focusing on:

(i) *a demand-driven approach to rural energy planning*: the choice of system should be based on the technology's ability to provide the most economical service consistent with energy needs such as power in household appliances. The choice should also reflect the willingness of customers to pay for services. The process should also allow rural energy service to be delivered through a range of institutes, including private sector agencies, local co-operatives and NGOs. The government can also facilitate access to credit lines, loan guarantees and other financing mechanisms.

(ii) *institutional and regulatory frameworks*: the Thai government should ensure a transparent, supportive institutional and regulatory framework to encourage market expansion. This can be done by rationalizing import duties and taxes, as well as incentive or subsidy programmes. The government should also ensure technical standards for PV components and systems, encourage a diversity of service providers, participate in programme implementation and disseminate information on PV technologies as well as the performance of SHS initiatives.

The strategy of promoting PV systems through institutions to local communities must be implemented in a number of different ways, depending on the degree of penetration of PV systems into an area. When PV is first introduced into an area in Thailand, the funding must come from outside the area, for example from the government and its agencies, in the form of demonstration projects. Local companies and individuals can be trained during these projects in installation and maintenance. Expansion of the PV programme can build on this experience to set up local installation companies. In the case that the cost of installation of the SHS is paid by the customers, the repayment period should ideally be short because the total interest charged will increase if the repayment period increases. To increase the number of households able to pay for SHS, the repayment strategy should be flexible. Financing can be organized through local co-operatives such as farmers' unions. It is possible to make payments in customers' products rather than cash. Rural households with irregular income streams may require seasonal rather than monthly payment schemes.

The strategic model for PV dissemination in Thailand proposed in this research programme has indicated that the national government is the principal player in the implementation of the strategy. One of the key points for the successful implementation is the national government must work hand in hand with other key players, such as international donor agencies, the electric utilities, educational/research institutes, the private sector and NGOs, with the full participation of the rural villages or communities for the successful dissemination of PV systems, particularly SHS projects, for the future in Thailand.

Appendix A

Solar Radiation on Selected Provinces of Thailand

The results come from the outcome of a computer programme that is developed with C-language for this project

Monthly average daily global radiation on inclined surfaces (kWh/m^2.day^{-1}) for Thailand
Province: Udon Thani Latitude : 17° 23′ N Longitude : 102° 43′ E

Degrees	Month												Annual
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
0	4.558	4.341	4.135	4.850	4.348	4.770	4.115	3.910	4.375	4.318	4.096	4.178	4.332
5	4.815	4.486	4.193	4.847	4.299	4.687	4.060	3.890	4.411	4.434	4.285	4.426	4.402
10	5.044	4.608	4.230	4.819	4.231	4.587	3.988	3.853	4.426	4.527	4.450	4.649	4.450
15	5.245	4.705	4.246	4.768	4.145	4.461	3.899	3.799	4.418	4.596	4.592	4.847	4.476
17	5.317	4.737	4.246	4.714	4.105	4.407	3.859	3.773	4.409	4.617	4.642	4.918	4.481
20	5.416	4.777	4.241	4.694	4.040	4.320	3.795	3.728	4.388	4.641	4.708	5.016	4.479
25	5.555	4.832	4.214	4.597	3.919	4.161	3.675	3.641	4.337	4.661	4.799	5.157	4.461
30	5.661	4.843	4.167	4.477	3.782	3.987	3.541	3.539	4.264	4.657	4.862	5.267	4.420
35	5.734	4.837	4.100	4.337	3.629	3.797	3.394	3.421	4.170	4.628	4.898	5.347	4.357
40	5.773	4.804	4.012	4.176	3.463	3.595	3.234	3.29	4.056	4.574	4.907	5.396	4.273
45	5.778	4.746	3.905	3.997	3.285	3.381	3.065	3.146	3.923	4.497	4.888	5.412	4.168
50	5.748	4.661	3.780	3.800	3.097	3.159	2.887	2.991	3.772	4.396	4.841	5.397	4.044
55	5.685	4.552	3.636	3.588	2.899	2.930	2.701	2.826	3.603	4.272	4.768	5.350	3.900
60	5.587	4.419	3.477	3.362	2.695	2.697	2.511	2.652	3.419	4.126	4.667	5.271	3.740
65	5.457	4.263	3.302	3.124	2.487	2.465	2.319	2.471	3.221	3.960	4.541	5.161	3.564
70	5.295	4.084	3.113	2.876	2.278	2.237	2.127	2.285	3.009	3.775	4.390	5.022	3.374
75	5.103	3.886	2.912	2.621	2.072	2.021	1.941	2.096	2.786	3.571	4.216	4.853	3.173
80	4.881	3.668	2.700	2.363	1.875	1.829	1.768	1.908	2.554	3.351	4.019	4.657	2.964
85	4.632	3.433	2.478	2.104	1.700	1.703	1.625	1.726	2.314	3.116	3.801	4.434	2.755
90	4.357	3.182	2.249	1.853	1.590	1.643	1.554	1.558	2.069	2.869	3.564	4.187	2.556

Monthly average daily global radiation on inclined surfaces (kWh/m^2.day^{-1}) for Thailand
Province: Chiang Rai Latitude : 19° 53′ N Longitude : 99° 50′ E

Degrees	Month												Annual
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
0	4.237	4.608	4.997	5.275	5.389	4.717	4.591	4.473	4.636	4.456	4.270	3.765	
5	4.492	4.792	5.096	5.283	5.328	4.645	4.532	4.456	4.688	4.596	4.501	4.013	4.702
10	4.721	4.950	5.167	5.265	5.243	4.553	4.454	4.419	4.716	4.712	4.707	4.239	4.762
15	4.924	5.081	5.211	5.219	5.133	4.443	4.357	4.361	4.720	4.802	4.886	4.441	4.789
20	5.099	5.183	5.227	5.147	4.999	4.315	4.241	4.283	4.700	4.867	5.038	4.617	4.809
25	5.244	5.257	5.215	5.050	4.843	4.167	4.108	4.185	4.655	4.905	5.161	4.766	4.796
30	5.358	5.301	5.175	4.927	4.665	4.004	3.957	4.069	4.587	4.917	5.254	4.887	4.758
35	5.441	5.314	5.107	4.779	4.468	3.826	3.792	3.934	4.496	4.901	5.317	4.979	4.696
40	5.491	5.298	5.012	4.609	4.252	3.634	3.613	3.783	4.382	4.859	5.348	5.042	4.610
45	5.509	5.252	4.890	4.417	4.020	3.431	3.421	3.615	4.247	4.791	5.348	5.074	4.500
50	5.494	5.176	4.743	4.205	3.773	3.218	3.218	3.434	4.091	4.696	5.317	5.075	4.370
55	5.446	5.071	4.571	3.974	3.514	2.998	3.008	3.24	3.915	4.577	5.255	5.046	4.218
60	5.366	4.939	4.376	3.727	3.246	2.773	2.790	3.036	3.722	4.433	5.163	4.987	4.046
65	5.255	4.778	4.160	3.465	2.972	2.545	2.570	2.822	3.512	4.266	5.040	4.898	3.857
70	5.113	4.592	3.923	3.192	2.696	2.320	2.349	2.601	3.287	4.078	4.889	4.779	3.651
75	4.940	4.382	3.669	2.909	2.422	2.103	2.132	2.377	3.048	3.868	4.709	4.633	3.432
80	4.740	4.148	3.398	2.620	2.158	1.901	1.927	2.151	2.799	3.640	4.504	4.459	3.203
85	4.513	3.893	3.113	2.329	1.916	1.733	1.744	1.930	2.54	3.395	4.273	4.260	2.970
90	4.260	3.619	2.816	2.043	1.724	1.653	1.630	1.720	2.274	3.135	4.020	4.036	2.744

Monthly average daily global radiation on inclined surfaces ($kWh/m^2.day^{-1}$) for Thailand

Province: Chiang Mai Latitude : 18° 47′ N Longitude : 98° 59′ E

Degrees	Month												Annual
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
0	4.469	4.698	5.345	5.491	5.511	4.787	4.571	4.369	4.671	4.694	4.704	4.322	4.802
5	4.735	4.879	5.450	5.495	5.443	4.709	4.509	4.350	4.719	4.840	4.965	4.606	4.891
10	4.974	5.033	5.525	5.470	5.349	4.611	4.428	4.310	4.743	4.960	5.198	4.863	4.955
15	5.185	5.160	5.570	5.418	5.230	4.493	4.328	4.251	4.742	5.054	5.401	5.093	4.993
20	5.366	5.258	5.584	5.337	5.087	4.357	4.209	4.172	4.718	5.119	5.573	5.293	5.006
25	5.515	5.326	5.568	5.230	4.921	4.203	4.073	4.074	4.669	5.157	5.712	5.461	4.992
30	5.632	5.365	5.521	5.096	4.733	4.033	3.920	3.958	4.596	5.166	5.817	5.597	4.952
35	5.715	5.373	5.445	4.936	4.525	3.847	3.753	3.825	4.500	5.147	5.887	5.700	4.887
40	5.764	5.351	5.338	4.753	4.298	3.648	3.571	3.676	4.382	5.099	5.923	5.768	4.797
45	5.779	5.289	5.203	4.547	4.054	3.438	3.378	3.512	4.242	5.023	5.923	5.801	4.683
50	5.759	5.216	5.040	4.320	3.797	3.218	3.174	3.334	4.082	4.920	5.888	5.800	4.545
55	5.705	5.105	4.851	4.073	3.527	2.991	2.963	3.144	3.902	4.790	5.817	5.762	4.385
60	5.616	4.966	4.637	3.810	3.249	2.759	2.745	2.944	3.705	4.635	5.712	5.690	4.205
65	5.495	4.799	4.399	3.532	2.965	2.527	2.525	2.736	3.491	4.455	5.573	5.584	4.006
70	5.341	4.606	4.139	3.243	2.680	2.297	2.305	2.521	3.262	4.252	5.402	5.444	3.711
75	5.155	4.389	3.860	2.943	2.399	2.077	2.091	2.303	3.021	4.028	5.199	5.272	3.561
80	4.940	4.149	3.564	2.639	2.130	1.876	1.889	2.085	2.768	3.784	4.966	5.069	3.321
85	4.697	3.888	3.252	2.333	1.887	1.720	1.716	1.871	2.507	3.522	4.705	4.836	3.077
90	4.427	3.607	2.928	2.034	1.716	1.654	1.623	1.672	2.238	3.243	4.418	4.576	2.844

Monthly average daily global radiation on inclined surfaces ($kWh/m^2.day^{-1}$) for Thailand

Province: Loei Latitude : 17° 27′ N Longitude : 101° 44′ E

Degrees	Month												Annual
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
0	4.201	4.479	4.857	5.031	5.097	4.636	4.528	4.427	4.125	4.118	4.109	3.997	4.467
5	4.424	4.634	4.937	5.028	5.032	4.558	4.463	4.403	4.158	4.225	4.300	4.227	4.532
10	4.622	4.765	4.992	5.001	4.944	4.460	4.378	4.359	4.170	4.309	4.468	4.434	4.575
15	4.795	4.870	5.020	4.948	4.833	4.344	4.275	4.294	4.162	4.372	4.612	4.617	4.595
20	4.941	4.948	5.021	4.870	4.701	4.209	4.154	4.210	4.134	4.412	4.731	4.774	4.592
25	5.059	5.000	4.997	4.769	4.548	4.058	4.015	4.107	4.085	4.429	4.823	4.903	4.566
30	5.148	5.024	4.945	4.644	4.375	3.891	3.861	3.985	4.017	4.423	4.888	5.004	4.517
35	5.207	5.020	4.868	4.497	4.184	3.710	3.691	3.846	3.929	4.394	4.925	5.077	4.445
40	5.236	4.989	4.766	4.329	3.976	3.516	3.509	3.690	3.824	4.340	4.935	5.120	4.352
45	5.235	4.930	4.639	4.142	3.753	3.312	3.315	3.520	3.700	4.268	4.917	5.133	4.238
50	5.203	4.845	4.489	3.936	3.518	3.098	3.111	3.336	3.559	4.172	4.871	5.116	4.104
55	5.142	4.733	4.316	3.713	3.273	2.879	2.900	3.141	3.403	4.054	4.798	5.069	3.951
60	5.051	4.596	4.122	3.476	3.020	2.655	2.683	2.935	3.233	3.916	4.698	4.993	3.781
65	4.931	4.434	3.909	3.226	2.763	2.432	2.464	2.721	3.049	3.759	4.572	4.888	3.595
70	4.783	4.250	3.677	2.966	2.505	2.212	2.247	2.502	2.853	3.585	4.421	4.755	3.396
75	4.608	4.043	3.429	2.699	2.252	2.003	2.037	2.280	2.647	3.393	4.246	4.595	3.186
80	4.408	3.816	3.167	2.427	2.011	1.816	1.842	2.058	2.433	3.186	4.048	4.409	2.968
85	4.183	3.571	2.892	2.156	1.800	1.690	1.683	1.844	2.211	2.965	3.830	4.199	2.752
90	3.936	3.310	2.668	1.892	1.676	1.628	1.611	1.648	1.984	2.733	3.591	3.966	2.548

Monthly average daily global radiation on inclined surfaces ($kWh/m^2.day^{-1}$) for Thailand

Province: Nakhon Pranom Latitude : 17° 25′ N Longitude : 104° 47′ E

Degrees	Month												Annual
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
0	4.268	4.284	4.601	4.810	4.887	4.299	4.239	4.183	4.345	4.471	4.578	4.253	4.434
5	4.497	4.427	4.673	4.807	4.827	4.231	4.181	4.161	4.381	4.595	4.811	4.510	4.508
10	4.701	4.546	4.721	4.781	4.744	4.145	4.106	4.121	4.396	4.696	5.017	4.743	4.559
15	4.879	4.641	4.745	4.73	4.641	4.042	4.013	4.061	4.388	4.771	5.195	4.948	4.588
20	5.029	4.711	4.744	4.657	4.516	3.923	3.904	3.983	4.359	4.821	5.343	5.125	4.593
25	5.151	4.757	4.718	4.561	4.372	3.789	3.778	3.888	4.308	4.845	5.46	5.273	4.575
30	5.243	4.776	4.669	4.444	4.209	3.640	3.638	3.775	4.236	4.844	5.548	5.389	4.534
35	5.304	4.769	4.595	4.305	4.029	3.478	3.485	3.646	4.144	4.816	5.599	5.474	4.47
40	5.335	4.737	4.498	4.147	3.833	3.304	3.319	3.503	4.031	4.726	5.619	5.526	4.384
45	5.334	4.679	4.378	3.970	3.624	3.121	3.142	3.345	3.899	4.683	5.607	5.545	4.277
50	5.304	4.596	4.237	3.775	3.402	2.929	2.956	3.175	3.749	4.579	5.562	5.532	4.149
55	5.242	4.489	4.074	3.566	3.170	2.731	2.763	2.994	3.583	4.451	5.485	5.485	4.002
60	5.150	4.357	3.893	3.342	2.931	2.530	2.566	2.803	3.400	4.300	5.375	5.406	3.837
65	5.028	4.204	3.693	3.107	2.688	2.328	2.365	2.605	3.203	4.127	5.235	5.296	3.656
70	4.877	4.028	3.477	2.862	2.444	2.128	2.166	2.402	2.994	3.934	5.064	5.154	3.460
75	4.699	3.833	3.246	2.610	2.204	1.938	1.973	2.195	2.773	3.721	4.865	4.982	3.253
80	4.494	3.619	3.002	2.354	1.976	1.767	1.793	1.990	2.543	3.491	4.639	4.781	3.037
85	4.265	3.387	2.746	2.098	1.775	1.648	1.644	1.791	2.306	3.246	4.387	4.554	2.820
90	4.013	3.141	2.481	1.849	1.655	1.585	1.572	1.608	2.063	2.986	4.112	4.300	2.614

Monthly average daily global radiation on inclined surfaces (kWh/m^2.day^{-1}) for Thailand

Province: Sakhon Nakhon Latitude : 17° 09′ N Longitude : 104° 08′ E

Degrees	Month												Annual
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
0	4.523	4.521	4.985	5.075	5.076	4.520	4.477	4.438	4.706	4.711	4.711	4.555	4.691
5	4.774	4.677	5.068	5.071	5.010	4.444	4.412	4.413	4.748	4.847	4.953	4.843	4.771
10	4.119	4.808	5.124	5.042	4.922	4.350	4.328	4.368	4.765	4.956	5.168	5.103	4.827
15	5.195	4.912	5.152	4.987	4.811	4.237	4.226	4.302	4.758	5.039	5.353	5.334	4.858
20	5.361	4.991	5.154	4.908	4.678	4.107	4.106	4.216	4.727	5.095	5.507	5.534	4.865
25	5.496	5.041	5.128	4.804	4.524	3.961	3.969	4.112	4.671	5.123	5.629	5.701	4.846
30	5.599	5.064	5.075	4.677	4.351	3.799	3.816	3.989	4.592	5.122	5.719	5.833	4.803
35	5.669	5.06	4.994	4.527	4.16	3.624	3.648	3.848	4.490	5.094	5.775	5.931	4.735
40	5.706	5.027	4.888	4.356	3.952	3.436	3.468	3.692	4.365	5.038	5.797	5.993	4.643
45	5.709	4.967	4.757	4.165	3.73	3.238	3.276	3.520	4.220	4.955	5.784	6.081	4.528
50	5.678	4.879	4.601	3.956	3.496	3.032	3.075	3.335	4.053	4.845	5.738	6.008	4.391
55	5.614	4.766	4.422	3.730	3.251	2.819	2.866	3.138	3.868	4.709	5.658	5.960	4.233
60	5.516	4.626	4.221	3.490	3.000	2.603	2.653	2.932	3.666	4.549	5.545	5.877	4.056
65	5.386	4.462	4.000	3.237	2.743	2.386	2.437	2.717	3.447	4.364	5.399	5.758	3.861
70	5.225	4.275	3.760	2.974	2.486	2.174	2.223	2.496	3.215	4.158	5.223	5.605	3.651
75	5.034	4.066	3.503	2.703	2.235	1.972	2.016	2.273	2.969	3.930	5.016	5.419	3.428
80	4.814	3.836	3.232	2.428	1.997	1.792	1.825	2.052	2.713	3.684	4.781	5.200	3.196
85	4.568	3.588	2.947	2.154	1.788	1.677	1.671	1.837	2.449	3.421	4.520	4.952	2.964
90	4.296	3.323	2.653	1.888	1.672	1.612	1.603	1.643	2.178	3.143	4.235	4.675	2.743

Monthly average daily global radiation on inclined surfaces (kWh/m^2.day^{-1}) for Thailand

Province: Phitsanulok Latitude : 16° 49′ N Longitude : 100° 16′ E

Degrees	Month												Annual
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
0	4.527	4.625	5.240	5.463	5.540	4.868	4.694	4.532	4.357	4.519	4.665	4.485	4.793
5	4.774	4.785	5.329	5.457	5.462	5.780	4.662	4.505	4.391	4.642	4.899	4.760	4.867
10	4.995	4.919	5.389	5.424	5.358	4.671	4.53	4.457	4.404	4.751	5.106	5.009	4.917
15	5.188	5.026	5.420	5.362	5.229	4.542	4.418	4.388	4.394	4.815	5.284	5.229	4.941
20	5.351	5.106	5.442	5.274	5.075	4.394	4.287	4.299	4.363	4.863	5.432	5.418	4.940
25	5.483	5.158	5.395	5.158	4.899	4.229	4.138	4.190	4.310	4.884	5.548	5.575	4.914
30	5.583	5.182	5.338	5.016	4.701	4.047	3.973	4.062	4.236	4.880	5.632	5.700	4.862
35	5.650	5.176	5.253	4.850	4.483	3.850	3.793	3.917	4.141	4.849	5.684	5.790	4.786
40	5.684	5.142	5.140	4.661	4.247	3.640	3.598	3.775	4.027	4.793	5.702	5.846	4.686
45	5.683	5.080	5.000	4.449	3.995	3.418	3.392	3.577	3.893	4.710	5.686	5.867	4.562
50	5.651	4.989	4.834	4.218	3.729	3.188	3.177	3.386	3.741	4.603	5.638	5.852	4.417
55	5.584	4.872	4.643	3.968	3.452	2.952	2.953	3.183	3.573	4.472	5.556	5.802	4.250
60	5.485	4.728	4.428	3.702	3.168	2.712	2.725	2.970	3.388	4.318	5.442	5.718	4.065
65	5.354	4.559	4.192	3.422	2.879	2.473	2.495	2.749	3.190	4.142	5.297	5.599	3.862
70	5.192	4.366	3.936	3.131	2.591	2.239	2.267	2.522	2.979	3.945	5.121	5.447	3.644
75	5.000	4.150	3.662	2.833	2.310	2.019	2.048	2.292	2.757	3.729	4.917	5.264	3.415
80	4.780	3.914	3.372	2.530	2.046	1.826	1.847	2.065	2.526	3.495	4.685	5.049	3.177
85	4.533	3.658	3.068	2.228	1.819	1.709	1.691	1.845	2.288	3.246	4.427	4.805	2.943
90	4.261	3.386	2.753	1.937	1.708	1.650	1.627	1.648	2.044	2.983	4.145	4.534	2.723

Monthly average daily global radiation on inclined surfaces (kWh/m^2.day^{-1}) for Thailand

Province: Khon Kaen Latitude : 16° 27′ N Longitude : 102° 50′ E

Degrees	Month												Annual
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
0	4.625	4.674	5.008	5.231	5.329	4.857	4.707	4.567	4.427	4.649	4.847	4.578	4.791
5	4.878	4.834	5.088	5.224	5.254	4.768	4.633	4.539	4.461	4.717	5.094	4.859	4.867
10	5.104	4.968	5.140	5.191	5.155	4.658	4.539	4.489	4.473	4.879	5.312	5.112	4.918
15	5.300	5.075	5.166	5.131	5.032	4.528	4.425	4.418	4.462	4.955	5.500	5.336	4.944
20	5.466	5.155	5.164	5.045	4.886	4.379	4.293	4.327	4.429	5.004	5.656	5.529	4.944
25	5.601	5.206	5.134	4.935	4.718	4.213	4.142	4.215	4.375	5.027	5.779	5.689	4.919
30	5.702	5.228	5.078	4.800	4.529	4.030	3.975	4.085	4.298	5.022	5.868	5.815	4.869
35	5.770	5.221	4.995	4.641	4.321	3.832	3.793	3.937	4.201	4.990	5.922	5.907	4.794
40	5.804	5.185	4.885	4.461	4.097	3.622	3.597	3.772	4.083	4.931	5.942	5.963	4.695
45	5.803	5.121	4.750	4.260	3.857	3.400	3.389	3.592	3.945	4.846	5.926	5.983	4.572
50	5.768	5.028	4.591	4.041	3.604	3.170	3.171	3.398	3.790	4.734	5.875	5.867	4.428
55	5.700	4.908	4.409	3.804	3.340	2.933	2.946	3.192	3.617	4.598	5.790	5.915	4.262
60	5.597	4.761	4.205	3.552	3.070	2.694	2.716	2.976	3.429	4.438	5.671	5.827	4.078
65	5.462	4.589	3.982	3.287	2.795	2.455	2.485	2.752	3.226	4.255	5.519	5.705	3.876
70	5.294	4.393	3.739	3.012	2.522	2.223	2.257	2.523	3.010	4.050	5.334	5.548	3.658
75	5.097	4.174	3.48	2.730	2.255	2.004	2.037	2.291	2.783	3.826	5.119	5.359	3.429
80	4.870	3.935	3.207	2.444	2.004	1.814	1.838	2.061	2.547	3.584	4.876	5.139	3.193
85	4.617	3.676	2.921	2.160	1.791	1.705	1.687	1.840	2.303	3.325	4.605	4.889	2.960
90	4.337	3.400	2.625	1.886	1.691	1.646	1.626	1.644	2.054	3.053	4.309	4.611	2.740

Monthly average daily global radiation on inclined surfaces (kWh/m^2.day^{-1}) for Thailand

Province: Roi Et Latitude : 16° 03′ N Longitude : 103° 41′ E

Degrees	Month												Annual
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
0	4.369	4.423	5.124	5.263	5.324	5.031	4.881	4.741	4.520	4.603	4.671	4.369	4.776
5	4.593	4.565	5.205	5.254	5.248	4.934	4.801	4.709	4.554	4.726	4.897	4.622	4.842
10	4.791	4.682	5.258	5.219	5.147	4.850	4.699	4.655	4.565	4.823	5.097	4.849	4.883
15	4.963	4.775	5.283	5.157	5.022	4.676	4.577	4.579	4.553	4.895	5.267	5.049	4.900
20	5.107	4.842	5.28	5.069	4.874	4.517	4.435	4.481	4.519	4.941	5.408	5.220	4.891
25	5.222	4.883	5.249	4.956	4.705	4.340	4.274	4.362	4.461	4.961	5.517	5.361	4.857
30	5.307	4.897	5.190	4.818	4.515	4.145	4.096	4.224	4.382	4.953	5.595	5.471	4.799
35	5.361	4.885	5.103	4.657	4.306	3.936	3.902	4.067	4.281	4.919	5.640	5.548	4.717
40	5.384	4.847	4.989	4.474	4.080	3.713	3.694	3.892	4.159	4.859	5.653	5.592	4.611
45	5.337	4.782	4.849	4.270	3.839	3.478	3.474	3.701	4.017	4.772	5.632	5.604	4.483
50	5.338	4.692	4.685	4.047	3.585	3.235	3.224	3.496	3.856	4.660	5.579	5.582	4.333
55	5.268	4.576	4.496	3.808	3.321	2.986	3.006	3.279	3.678	4.524	5.493	5.528	4.163
60	5.168	4.437	4.286	3.553	3.050	2.734	2.764	3.051	3.484	4.365	5.376	5.441	3.975
65	5.038	4.274	4.055	3.285	2.775	2.484	2.521	2.815	3.275	4.183	5.227	5.321	3.771
70	4.880	4.090	3.805	3.008	2.502	2.241	2.282	2.573	3.053	3.980	5.049	5.171	3.552
75	4.695	3.885	3.537	2.723	2.236	2.013	2.053	2.329	2.819	3.759	4.843	4.991	3.323
80	4.483	3.661	3.255	2.435	1.987	1.819	1.847	2.089	2.576	3.519	4.610	4.783	3.088
85	4.248	3.421	2.961	2.148	1.779	1.717	1.700	1.858	2.326	3.264	4.352	4.547	2.86
90	3.989	3.165	2.655	1.874	1.688	1.660	1.642	1.657	2.070	2.995	4.071	4.287	2.646

Monthly average daily global radiation on inclined surfaces (kWh/m^2.day^{-1}) for Thailand

Province: Nakhon Sawan Latitude : 15° 40′ N Longitude : 100° 07′ E

Degrees	Month												Annual
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
0	4.560	4.661	5.136	5.233	5.238	4.682	4.532	4.392	4.287	4.473	4.643	4.508	4.695
5	4.797	4.814	5.215	5.223	5.162	4.595	4.460	4.363	4.316	4.587	4.863	4.771	4.764
10	5.008	4.942	5.266	5.186	5.062	4.489	4.369	4.314	4.324	4.677	5.056	5.007	4.808
15	5.191	5.043	5.290	5.123	4.939	4.364	4.260	4.244	4.310	4.742	5.221	5.215	4.828
20	5.344	5.116	5.285	5.034	4.793	4.221	4.132	4.156	4.276	4.782	5.356	5.392	4.823
25	5.466	5.161	5.251	4.920	4.626	4.060	3.987	4.048	4.220	4.797	5.460	5.538	4.794
30	5.557	5.178	5.190	4.782	4.439	3.885	3.827	3.923	4.144	4.786	5.533	5.652	4.741
35	5.615	5.167	5.101	4.620	4.233	3.695	3.652	3.780	4.047	4.750	5.574	5.732	4.664
40	5.641	5.126	4.986	4.437	4.011	3.493	3.464	3.622	3.932	4.689	5.583	5.778	4.563
45	5.633	5.058	4.844	4.234	3.774	3.280	3.265	3.450	3.789	4.603	5.560	5.790	4.440
50	5.593	4.962	4.678	4.012	3.525	3.060	3.057	3.264	3.647	4.493	5.504	5.767	4.296
55	5.520	4.840	4.488	3.773	3.266	2.834	2.842	3.068	3.480	4.360	5.417	5.710	4.133
60	5.414	4.691	4.276	3.519	3.000	2.605	2.623	2.861	3.297	4.204	5.298	5.619	3.950
65	5.278	4.518	4.043	3.253	2.731	2.377	2.403	2.648	3.102	4.028	5.150	5.495	3.752
70	5.111	4.321	3.792	2.977	2.463	2.156	2.186	2.429	2.894	3.832	4.972	5.339	3.539
75	4.915	4.102	3.523	2.694	2.203	1.949	1.978	2.209	2.676	3.617	4.767	5.151	3.315
80	4.692	3.862	3.240	2.408	1.961	1.773	1.791	1.992	2.450	3.387	4.535	4.934	3.085
85	4.443	3.605	2.945	2.124	1.761	1.681	1.662	1.784	2.216	3.141	4.279	4.689	2.860
90	4.170	3.330	2.638	1.853	1.679	1.622	1.601	1.603	1.978	2.882	4.001	4.418	2.648

Monthly average daily global radiation on inclined surfaces (kWh/m^2.day^{-1}) for Thailand

Province: Ubon Ratchathani Latitude : 15° 15′ N Longitude : 104° 52′ E

Degrees	Month												Annual
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
0	4.624	4.732	5.229	5.208	5.167	4.915	4.735	4.567	4.404	4.571	4.723	4.567	4.786
5	4.863	4.887	5.308	5.196	5.091	4.818	4.656	4.535	4.433	4.687	4.946	4.831	4.854
10	5.075	5.015	5.359	5.157	4.992	4.701	4.556	4.481	4.441	4.779	5.141	5.068	4.897
15	5.258	5.116	5.382	5.093	4.869	4.564	4.437	4.406	4.426	4.845	5.307	5.276	4.914
20	5.411	5.189	5.375	5.003	4.725	4.407	4.298	4.311	4.389	4.885	5.443	5.453	4.907
25	5.533	5.234	5.340	4.888	4.559	4.233	4.142	4.196	4.330	4.900	5.548	5.600	4.875
30	5.623	5.250	5.276	4.749	4.374	4.042	3.969	4.062	4.250	4.888	5.621	5.712	4.818
35	5.680	5.236	5.184	4.587	4.171	3.836	3.781	3.910	4.150	4.850	5.661	5.790	4.736
40	5.704	5.194	5.064	4.404	3.951	3.618	3.579	3.742	4.030	4.786	5.668	5.835	4.631
45	5.695	5.123	4.919	4.201	3.718	3.389	3.366	3.559	3.890	4.697	5.643	5.845	4.503
50	5.652	5.025	4.747	3.979	3.472	3.151	3.144	3.363	3.733	4.583	5.585	5.820	4.354
55	5.576	4.899	4.552	3.740	3.217	2.909	2.915	3.154	3.559	4.446	5.494	5.760	4.185
60	5.468	4.746	4.334	3.487	2.955	2.664	2.681	2.936	3.370	4.285	5.372	5.666	3.997
65	5.328	4.569	4.095	3.222	2.690	2.420	2.447	2.711	3.167	4.103	5.220	5.539	3.792
70	5.158	4.368	3.837	2.947	2.427	2.185	2.218	2.480	2.951	3.901	5.038	5.379	3.574
75	4.958	4.144	3.562	2.666	2.172	1.967	2.000	2.248	2.725	3.681	4.827	5.188	3.344
80	4.731	3.900	3.272	2.382	1.936	1.785	1.805	2.020	2.490	3.443	4.591	4.967	3.110
85	4.477	3.637	2.969	2.101	1.745	1.701	1.681	1.803	2.248	3.191	4329	4.718	2.883
90	4.200	3.357	2.655	1.833	1.671	1.643	1.622	1.617	2.001	2.925	4.045	4.443	2.667

Monthly average daily global radiation on inclined surfaces (kWh/m^2.day^{-1}) for Thailand

Province: Nakhon Ratchasima Latitude : 14° 58′ N Longitude : 102° 05′ E

Degrees	Month												Annual
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
0	4.555	4.644	5.054	5.124	5.114	4.892	4.778	4.671	4.404	4.536	4.655	4.508	4.744
5	4.784	4.791	5.127	5.111	5.038	4.795	4.696	4.636	4.432	4.649	4.869	4.762	4.807
10	4.987	4.913	5.173	5.072	4.939	4.677	4.594	4.580	4.438	4.737	5.056	4.990	4.846
15	5.162	5.008	5.191	5.008	4.817	4.540	4.471	4.501	4.423	4.801	5.214	5.189	4.860
20	5.308	5.076	5.182	4.919	4.674	4.383	4.330	4.402	4.385	4.838	5.344	5.359	4.850
25	5.423	5.116	5.146	4.805	4.510	4.209	4.170	4.282	4.325	4.851	5.443	5.498	4.814
30	5.507	5.129	5.082	4.668	4.326	4.018	3.994	4.143	4.245	4.837	5.510	5.604	4.755
35	5.559	5.113	4.992	4.509	4.125	3.813	3.802	3.986	4.143	4.789	5.546	5.677	4.672
40	5.579	5.069	4.875	4.328	3.908	3.595	3.597	3.811	4.022	4.733	5.550	5.717	4.565
45	5.567	4.998	4.734	4.128	3.677	3.367	3.381	3.622	3.882	4.643	5.523	5.724	4.437
50	5.522	4.899	4.568	3.911	3.434	3.130	3.155	3.418	3.724	4.530	5.463	5.696	4.287
55	5.445	4.775	4.380	3.677	3.181	2.888	2.922	3.203	3.550	4.392	5.372	5.635	4.118
60	5.337	4.624	4.170	3.428	2.923	2.646	2.685	2.977	3.360	4.233	5.250	5.540	3.931
65	5.198	4.450	3.941	3.168	2.661	2.403	2.448	2.745	3.156	4.052	5.099	5.413	3.727
70	5.029	4.253	3.694	2.899	2.402	2.169	2.216	2.507	2.940	3.851	4.919	5.255	3.511
75	4.833	4.034	3.430	2.623	2.151	1.953	1.996	2.268	2.714	3.633	4.712	5.066	3.284
80	4.609	3.796	3.153	2.345	1.919	1.776	1.801	2.033	2.479	3.397	4.479	4.848	3.053
85	4.361	3.539	2.863	2.071	1.734	1.696	1.683	1.811	2.237	3.147	4.223	4.603	2.830
90	4.089	3.267	2.564	1.810	1.665	1.639	1.625	1.624	1.990	2.884	3.944	4.333	2.619

Monthly average daily global radiation on inclined surfaces (kWh/m^2.day^{-1}) for Thailand

Province: Surin Latitude : 14° 53′ N Longitude : 103° 30′ E

Degrees	Month												Annual
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
0	4.648	4.746	5.275	5.171	5.074	4.822	4.774	4.729	4.613	4.684	4.747	4.601	4.823
5	4.885	4.899	5.354	5.157	5.000	4.727	4.692	4.693	4.644	4.803	4.968	4.864	4.890
10	5.095	5.025	5.404	5.118	4.901	4.612	4.590	4.635	4.651	4.897	5.161	5.099	4.932
15	5.276	5.124	5.425	5.052	4.780	4.477	4.467	4.555	3.635	4.965	5.325	5.306	4.950
20	5.427	5.195	5.416	4.962	4.638	4.324	4.325	4.453	4.596	5.006	5.459	5.482	4.940
25	5.547	5.238	5.379	4.846	4.476	4.153	4.166	4.331	4.533	5.020	5.562	5.626	4.906
30	5.635	5.252	5.313	4.707	4.294	3.966	3.989	4.190	4.448	5.008	5.633	5.736	4.847
35	5.689	5.236	5.218	4.546	4.095	3.765	3.797	4.029	4.340	4.968	5.671	5.813	4.764
40	5.711	5.192	5.096	4.363	3.880	3.552	3.592	3.852	4.212	4.902	5.676	5.856	4.657
45	5.699	5.120	4.947	4.160	3.651	3.328	3.376	3.659	4.063	4.809	5.548	5.863	4.527
50	5.654	5.019	4.773	3.940	3.410	3.096	3.150	3.451	3.896	4.691	5.588	5.836	4.375
55	5.576	4.891	4.575	3.703	3.160	2.858	2.917	3.232	3.711	4.549	5.495	5.774	4.203
60	5.466	4.737	4.353	3.451	2.904	2.619	2.681	3.003	3.509	4.383	5.371	5.678	4.013
65	5.324	4.558	4.111	3.188	2.646	2.382	2.444	2.766	3.292	4.195	5.216	5.548	3.806
70	5.151	4.356	3.850	2.915	2.389	2.153	2.212	2.524	3.063	3.987	5.032	5.386	3.584
75	4.950	4.131	3.571	2.636	2.140	1.941	1.992	2.281	2.822	3.759	4.820	5.192	3.353
80	4.721	3.886	3.277	2.355	1.911	1.767	1.798	2.043	2.572	3.513	4.582	4.969	3.116
85	4.466	3.622	2.971	2.077	1.729	1.689	1.682	1.817	2.314	3.253	4.318	4.718	2.888
90	4.187	3.341	2.653	1.814	1.661	1.631	1.624	1.629	2.052	2.978	4.033	4.440	2.670

Monthly average daily global radiation on inclined surfaces (kWh/m^2.day^{-1}) for Thailand

Province: Bangkok Latitude : 13° 44′ N Longitude : 100° 30′ E

Degrees	Month												Annual
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
0	4.641	4.713	5.403	5.124	4.906	4.613	4.451	4.299	4.136	4.346	4.545	4.625	4.650
5	4.865	4.855	5.478	5.106	4.831	4.521	4.375	4.265	4.157	4.443	4.738	4.876	4.709
10	5.062	4.972	5.524	5.062	4.733	4.410	4.280	4.212	4.156	4.518	4.905	5.100	4.744
15	5.231	5.062	5.541	4.992	4.614	4.280	4.167	4.139	4.138	4.569	5.046	5.296	4.756
20	5.370	5.124	5.527	4.898	4.475	4.133	4.036	4.047	4.098	4.596	5.158	5.461	4.743
25	5.479	5.158	5.483	4.780	4.316	3.969	3.889	3.938	4.039	4.599	5.242	5.594	4.707
30	5.556	5.165	5.410	4.638	4.139	3.790	3.726	3.811	3.960	4.579	5.296	5.694	4.647
35	5.601	5.143	5.308	4.475	3.945	3.518	3.550	3.668	3.863	4.535	5.320	5.761	4.564
40	5.614	5.093	5.178	4.290	3.736	3.395	3.362	3.509	3.748	4.467	5.314	5.795	4.458
45	5.594	5.015	5.020	4.086	3.515	3.181	3.163	3.338	3.615	4.376	5.278	5.794	4.331
50	5.542	4.911	4.837	3.865	3.282	2.961	2.956	3.154	3.467	4.263	5.212	5.759	4.184
55	5.458	4.780	4.629	3.628	3.041	2.735	2.742	2.959	3.304	4.129	5.117	5.690	4.017
60	5.342	4.624	4.398	3.377	2.795	2.509	2.526	2.756	3.127	3.974	4.993	5.587	3.834
65	5.197	4.443	4.146	3.115	2.546	2.285	2.310	2.546	2.938	3.800	4.842	5.452	3.635
70	5.021	4.240	3.874	2.844	2.301	2.070	2.099	2.333	2.738	3.608	4.664	5.286	3.423
75	4.818	4.016	3.585	2.568	2.064	1.874	1.900	2.119	2.529	3.400	4.461	5.089	3.202
80	4.589	3.773	3.281	2.290	1.850	1.721	1.730	1.909	2.312	3.177	4.235	4.863	2.977
85	4.335	3.512	2.965	2.018	1.696	1.659	1.640	1.713	2.090	2.941	3.986	4.611	2.763
90	4.058	3.235	2.638	1.764	1.638	1.600	1.580	1.559	1.864	2.693	3.718	4.333	2.556

Monthly average daily global radiation on inclined surfaces (kWh/m^2.day^{-1}) for Thailand

Province: Chantaburi Latitude : 12° 36′ N Longitude : 102° 07′ E

Degrees	Month												Annual
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
0	4.742	4.743	5.089	4.803	4.571	4.183	4.045	3.916	3.811	4.218	4.606	4.764	4.457
5	4.963	4.879	5.150	4.782	4.501	4.103	3.978	3.885	3.825	4.304	4.794	5.016	4.515
10	5.157	4.989	5.185	4.738	4.410	4.005	3.894	3.836	3.821	4.368	4.955	5.239	4.550
15	5.321	5.073	5.192	4.670	4.300	3.891	3.794	3.770	3.799	4.411	5.090	5.433	4.562
20	5.456	5.129	5.172	4.580	4.171	3.762	3.679	3.688	3.760	4.430	5.196	5.595	4.551
25	5.560	5.157	5.124	4.468	4.024	3.618	3.549	3.589	3.703	4.427	5.274	5.726	4.518
30	5.631	5.158	5.050	4.334	3.861	3.461	3.406	3.476	3.629	4.401	5.322	5.822	4.462
35	5.671	5.130	4.949	4.181	3.683	3.292	3.250	3.348	3.538	4.353	5.339	5.885	4.385
40	5.677	5.075	4.823	4.008	3.491	3.113	3.084	3.207	3.432	4.283	5.327	5.913	4.286
45	5.651	4.992	4.672	3.819	3.288	2.925	2.908	3.054	3.310	4.191	5.285	5.906	4.167
50	5.592	4.882	4.498	3.613	3.075	2.731	2.725	2.891	3.175	4.078	5.213	5.864	4.028
55	5.501	4.746	4.301	3.393	2.854	2.533	2.537	2.718	3.027	3.946	5.112	5.787	3.871
60	5.379	4.586	4.084	3.161	2.629	2.334	2.347	2.538	2.866	3.794	4.983	5.677	3.698
65	5.226	4.402	3.848	2.919	2.402	2.138	2.156	2.352	2.696	3.624	4.826	5.534	3.510
70	5.044	4.195	3.595	2.670	2.179	1.949	1.971	2.163	2.515	3.438	4.643	5.359	3.310
75	4.834	3.968	3.327	2.415	1.965	1.780	1.797	1.974	2.327	3.237	4.435	5.153	3.101
80	4.597	3.722	3.046	2.161	1.774	1.660	1.652	1.790	2.133	3.022	4.204	4.918	2.890
85	4.336	3.459	2.753	1.913	1.656	1.599	1.580	1.620	1.934	2.795	3.952	4.655	2.687
90	4.052	3.181	2.452	1.686	1.596	1.538	1.518	1.501	1.731	2.558	3.680	4.368	2.488

Monthly average daily global radiation on inclined surfaces (kWh/m^2.day^{-1}) for Thailand

Province: Phuket Latitude : 07° 53′ N Longitude : 99° 38′ E

Degrees	Month												Annual
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
0	4.844	5.140	5.507	4.907	4.496	4.392	4.362	4.334	4.113	4.268	4.422	4.624	4.617
5	5.029	5.264	5.552	4.867	4.410	4.284	4.266	4.281	4.116	4.335	4.561	4.816	4.648
10	5.186	5.360	5.567	4.802	4.303	4.158	4.152	4.208	4.099	4.380	4.677	4.981	4.656
15	5.315	5.427	5.553	4.714	4.178	4.015	4.020	4.115	4.062	4.403	4.767	5.120	4.641
20	5.415	5.465	5.508	4.603	4.035	3.856	3.872	4.004	4.006	4.404	4.833	5.230	4.603
25	5.485	5.473	5.435	4.470	3.875	3.642	3.708	3.875	3.932	4.383	4.872	5.311	4.542
30	5.524	5.451	5.332	4.316	3.699	3.495	3.531	3.730	3.838	4.340	4.886	5.363	4.458
35	5.532	5.399	5.201	4.142	3.510	3.297	3.341	3.569	3.727	4.275	4.873	5.384	4.354
40	5.509	5.319	5.044	3.950	3.309	3.089	3.140	3.393	3.600	4.189	4.835	5.376	4.230
45	5.455	5.209	4.860	3.740	3.097	2.874	2.932	3.205	3.456	4.082	4.770	5.337	4.085
50	5.371	5.072	4.652	3.516	2.877	2.655	2.717	3.007	3.298	3.956	4.680	5.268	3.922
55	5.257	4.908	4.422	3.279	2.653	2.435	2.500	2.799	3.126	3.811	4.565	5.170	3.744
60	5.114	4.719	4.170	3.031	2.426	2.218	2.283	2.585	2.942	3.648	4.427	5.044	3.550
65	4.943	4.505	3.898	2.774	2.203	2.011	2.072	2.367	2.747	3.469	4.266	4.889	3.345
70	4.746	4.269	3.610	2.512	1.988	1.825	1.876	2.148	2.543	3.275	4.083	4.709	3.132
75	4.524	4.012	3.307	2.250	1.796	1.693	1.714	1.936	2.331	3.068	3.881	4.503	2.918
80	4.278	3.737	2.991	1.993	1.672	1.638	1.641	1.739	2.114	2.848	3.659	4.274	2.715
85	4.011	3.445	2.665	1.757	1.615	1.582	1.584	1.603	1.893	2.618	3.421	4.023	2.518
90	3.725	3.139	2.331	1.622	1.558	1.526	1.527	1.544	1.671	2.380	3.168	3.752	2.328

Monthly average daily global radiation on inclined surfaces (kWh/m^2.day^{-1}) for Thailand

Province: Songkha Latitude : 07° 14′ N Longitude : 100° 07′ E

Degrees	Month												Annual
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
0	4.496	4.990	5.368	5.054	4.824	4.636	4.678	4.717	4.415	4.235	4.068	4.113	4.633
5	4.652	5.103	5.407	5.009	4.723	4.514	4.566	4.625	4.417	4.298	4.183	4.262	4.649
10	4.783	5.190	5.418	4.939	4.600	4.372	4.434	4.566	4.396	4.340	4.276	4.389	4.642
15	4.889	5.249	5.400	4.844	4.456	4.212	4.283	4.457	4.355	4.360	4.348	4.493	4.612
20	4.969	5.279	5.354	4.725	4.293	4.035	4.113	4.328	4.292	4.358	4.398	4.574	4.560
25	5.022	5.282	5.279	4.584	4.111	3.842	3.927	4.179	4.208	4.334	4.424	4.630	4.485
30	5.048	5.256	5.176	4.421	3.913	3.636	3.727	4.011	4.104	4.289	4.428	4.661	4.389
35	5.046	5.201	5.047	4.237	3.700	3.417	3.513	3.827	3.980	4.223	4.409	4.668	4.272
40	5.017	5.120	4.891	4.034	3.474	3.190	3.288	3.626	3.838	4.135	4.367	4.648	4.136
45	4.961	5.010	4.711	3.814	3.237	2.955	3.054	3.412	3.679	4.028	4.303	4.606	3.981
50	4.878	4.875	4.508	3.578	2.992	2.716	2.815	3.187	3.504	3.901	4.217	4.538	3.809
55	4.769	4.714	4.283	3.330	2.743	2.478	2.574	2.951	3.314	3.756	4.109	4.446	3.622
60	4.634	4.530	4.037	3.070	2.493	2.244	2.335	2.709	3.110	3.594	3.981	4.331	3.422
65	4.475	4.322	3.774	2.802	2.246	2.023	2.104	2.464	2.895	3.416	3.833	4.193	3.212
70	4.293	4.094	3.494	2.529	2.013	1.828	1.893	2.219	2.670	3.223	3.667	4.034	2.996
75	4.090	3.846	3.200	2.255	1.808	1.705	1.725	1.983	2.436	3.017	3.484	3.855	2.784
80	3.866	3.581	2.894	1.990	1.695	1.653	1.663	1.769	2.197	2.799	3.285	3.657	2.587
85	3.624	3.301	2.579	1.751	1.641	1.599	1.609	1.640	1.953	2.572	3.071	3.442	2.398
90	3.365	3.007	2.257	1.633	1.587	1.545	1.555	1.584	1.710	2.336	2.845	3.211	2.220

Solar Altitude Angle (α) for Thailand between 6° through 20° latitude (Northern Latitude)

Date and declination	Solar time a.m. , p.m.	Latitude 6°	7°	8°	9°	10°	11°	12°	13°	14°	15°	16°	17°	18°	19°	20°
June 21ST	Noon	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87
23.5°	11 1	67	68	69	70	70	71	71	72	73	73	74	74	74	75	75
	10 2	56	57	57	57	58	58	59	59	60	60	61	61	61	62	62
	9 3	43	44	44	44	45	45	45	46	46	46	47	47	47	48	48
	8 4	30	31	31	31	31	31	32	32	32	32	33	33	34	34	34
	7 5	16	17	17	17	18	18	18	19	19	20	20	20	20	21	21
	6 6	2	3	3	3	4	4	4	5	5	5	6	6	7	7	8
May 21ST	Noon	76	77	78	79	80	81	82	83	84	85	86	86	86	86	86
or	11 1	70	71	71	71	72	72	73	73	74	74	75	75	75	75	75
July 21ST	10 2	58	58	59	59	59	60	60	60	60	61	61	61	61	61	61
20°	9 3	44	45	45	45	45	46	46	46	46	47	47	47	47	47	48
	8 4	30	31	31	31	31	32	32	32	32	33	33	33	33	33	34
	7 5	16	17	17	17	17	18	18	18	19	19	19	19	19	19	20
	6 6	2	3	3	3	3	4	4	4	4	5	5	6	6	6	7
April 21ST	Noon	84	85	86	86	86	86	86	86	86	86	86	85	84	83	82
or	11 1	74	75	75	75	75	75	75	75	75	75	75	75	74	74	73
Aug 21ST	10 2	60	60	60	60	60	60	60	61	61	61	61	61	61	60	60
12°	9 3	45	46	46	46	46	46	46	46	46	46	46	46	46	46	46
	8 4	33	33	34	34	34	33	33	33	32	32	32	32	32	32	32
	7 5	16	16	16	16	16	16	16	17	17	17	17	17	17	17	17
	6 6	2	2	2	2	2	2	2	2	3	3	3	3	3	4	4
March 21ST	Noon	84	83	82	81	80	79	78	77	76	75	74	73	72	71	70
or	11 1	73	73	73	72	72	71	71	70	69	69	68	67	66	66	65
Sept 21ST	10 2	59	59	59	59	58	58	57	57	57	56	56	56	55	55	54
0°	9 3	44	44	44	44	44	44	44	43	43	43	43	43	42	42	41
	8 4	30	30	30	30	30	30	30	29	29	29	29	29	29	28	28
	7 5	15	15	15	15	15	15	15	14	14	14	14	14	14	14	14
	6 6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Feb 21ST	Noon	71	71	71	70	69	68	67	66	65	64	63	62	61	60	59
or	11 1	67	67	66	65	64	63	62	62	61	60	59	58	57	56	55
Oct 21ST	10 2	56	55	55	54	54	53	53	52	51	51	50	49	49	48	47
- 11°	9 3	42	41	41	41	40	40	40	39	39	38	38	38	38	37	37
	8 4	28	27	27	27	27	27	26	26	26	26	25	25	24	24	24
	7 5	13	13	13	13	13	12	12	12	12	11	11	11	11	11	10
Jan 21ST	Noon	64	63	62	61	60	59	58	57	56	55	54	53	52	51	50
or	11 1	60	59	58	57	56	55	55	54	53	52	51	50	49	48	47
Nov. 21	10 2	50	50	49	48	48	47	46	45	45	44	43	42	42	41	40
- 20°	9 3	39	38	38	37	37	36	36	35	34	34	33	32	32	31	31
	8 4	26	25	25	25	24	24	23	23	22	22	21	21	20	20	19
	7 5	12	11	11	11	10	10	10	9	9	9	8	8	7	7	6
DEC 21ST	Noon	60	59	58	57	56	55	55	54	53	52	51	50	49	48	47
- 23.5°	11 1	57	56	55	54	53	52	52	51	50	49	48	49	46	45	43
	10 2	49	48	47	46	46	45	44	43	43	42	41	40	39	38	37
	9 3	37	36	36	35	35	34	34	33	32	32	31	30	30	29	28
	8 4	24	23	23	23	22	22	21	21	20	20	19	19	18	18	17
	7 5	11	10	10	10	9	9	9	8	8	7	7	7	6	6	5

Solar Azimuth Angle (ϕ) for Thailand between 6° through 20° latitude (Northern Latitude)

Date and declination	Solar time a.m. , p.m.	Latitude 6°	7°	8°	9°	10°	11°	12°	13°	14°	15°	16°	17°	18°	19°	20°
June 21ST	Noon	180	180	180	180	180	180	180	180	180	180	180	180	180	180	180
23.5°	11 1	141	140	139	137	134	132	130	127	125	122	120	116	113	109	106
	10 2	124	123	122	121	119	118	116	115	113	112	110	108	106	104	102
	9 3	117	116	115	114	113	112	112	111	110	109	108	107	106	105	104
	8 4	114	113	113	113	112	112	112	111	111	110	110	110	109	109	109
	7 5	113	112	112	112	112	112	112	113	113	113	113	112	112	111	111
	6 6	113	113	113	113	113	113	113	113	113	113	113	113	113	113	113
May 21ST	Noon	180	180	180	180	180	180	180	180	180	180	180	180	180	180	180
or	11 1	135	133	131	128	125	122	120	117	114	111	108	104	100	96	93
July 21ST	10 2	119	117	116	114	113	111	110	108	106	105	103	101	99	97	96
20°	9 3	112	111	110	109	108	107	106	105	104	103	102	101	100	99	98
	8 4	110	109	109	108	108	107	107	107	105	105	104	103	103	102	101
	7 5	110	109	109	109	108	108	108	107	107	106	106	106	107	107	107
	6 6	110	110	110	110	110	110	110	109	109	109	109	109	109	109	108
April 21ST	Noon	180	180	180	180	180	180	180	0	0	0	0	0	0	0	0
or	11 1	112	109	106	102	99	95	92	88	84	81	77	74	71	68	65
Aug 21ST	10 2	103	102	100	98	97	95	93	91	90	88	86	84	83	81	79
12°	9 3	101	100	99	98	97	96	95	94	93	92	91	90	89	88	86
	8 4	100	100	99	98	98	97	97	96	95	95	94	93	93	92	92
	7 5	101	100	100	100	100	99	99	99	97	98	98	98	97	97	96
	6 6	102	102	102	102	102	102	102	102	102	102	102	102	102	102	102
March 21ST	Noon	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
or	11 1	70	66	63	61	58	56	54	51	49	46	44	43	41	40	38
Sept 21ST	10 2	80	78	76	75	73	72	70	69	67	66	64	63	62	61	60
0°	9 3	81	81	81	81	80	79	79	78	77	76	75	74	73	72	71
	8 4	87	86	85	85	84	84	83	83	82	82	81	81	80	80	79
	7 5	89	88	88	88	88	87	87	87	87	86	86	86	86	85	85
	6 6	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90
Feb 21ST	Noon	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
or	11 1	42	40	38	37	36	35	34	33	32	31	30	29	29	28	27
Oct 21ST	10 2	61	59	58	57	56	55	54	53	52	51	50	49	48	47	47
-11°	9 3	70	69	68	67	67	66	65	64	64	63	62	61	61	60	60
	8 4	74	73	73	73	72	72	71	71	70	70	69	69	68	68	68
	7 5	78	77	77	77	77	76	76	76	76	75	75	75	75	75	75
Jan 21ST	Noon	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
or	11 1	30	29	28	27	27	26	26	25	24	24	23	23	22	22	22
Nov 21ST	10 2	48	47	46	45	45	44	43	42	42	41	40	40	39	39	38
-20°	9 3	59	58	57	56	56	55	55	54	53	53	52	52	51	51	51
	8 4	65	64	64	64	63	63	63	62	62	61	61	61	61	61	60
	7 5	68	68	68	67	67	67	67	66	66	66	66	66	66	66	66
Dec 21ST	Noon	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-23.5°	11 1	27	26	25	25	25	24	24	23	22	22	21	21	20	20	20
	10 2	44	43	42	41	41	40	40	39	38	38	37	37	36	36	36
	9 3	54	54	53	53	52	52	51	51	50	50	49	49	48	48	48
	8 4	61	60	60	60	59	59	59	58	58	57	57	57	57	56	56
	7 5	64	64	64	64	64	64	64	63	63	63	63	63	63	63	63

Appendix B

Flow Diagram of the Computer Programmes

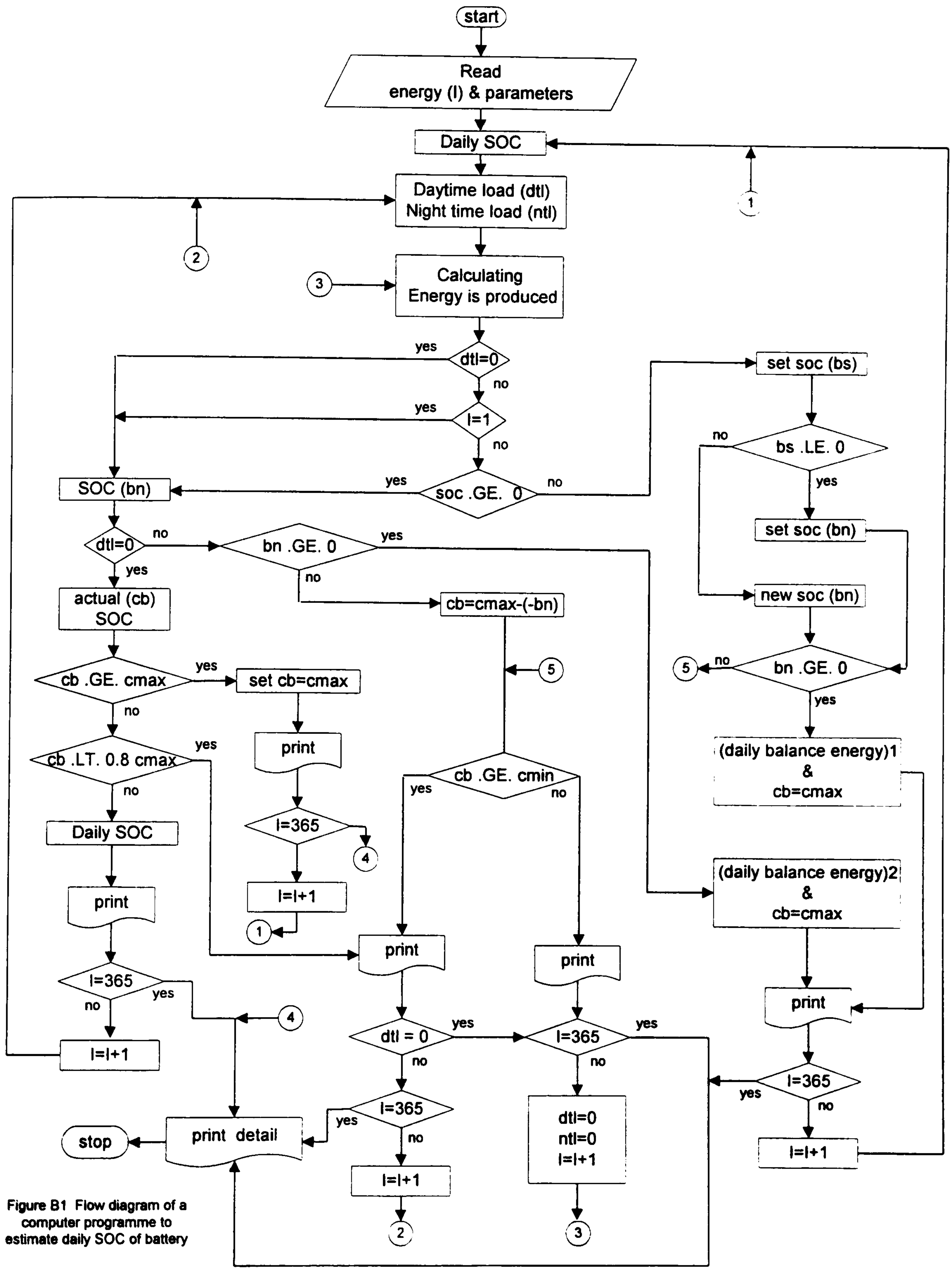


Figure B1 Flow diagram of a computer programme to estimate daily SOC of battery

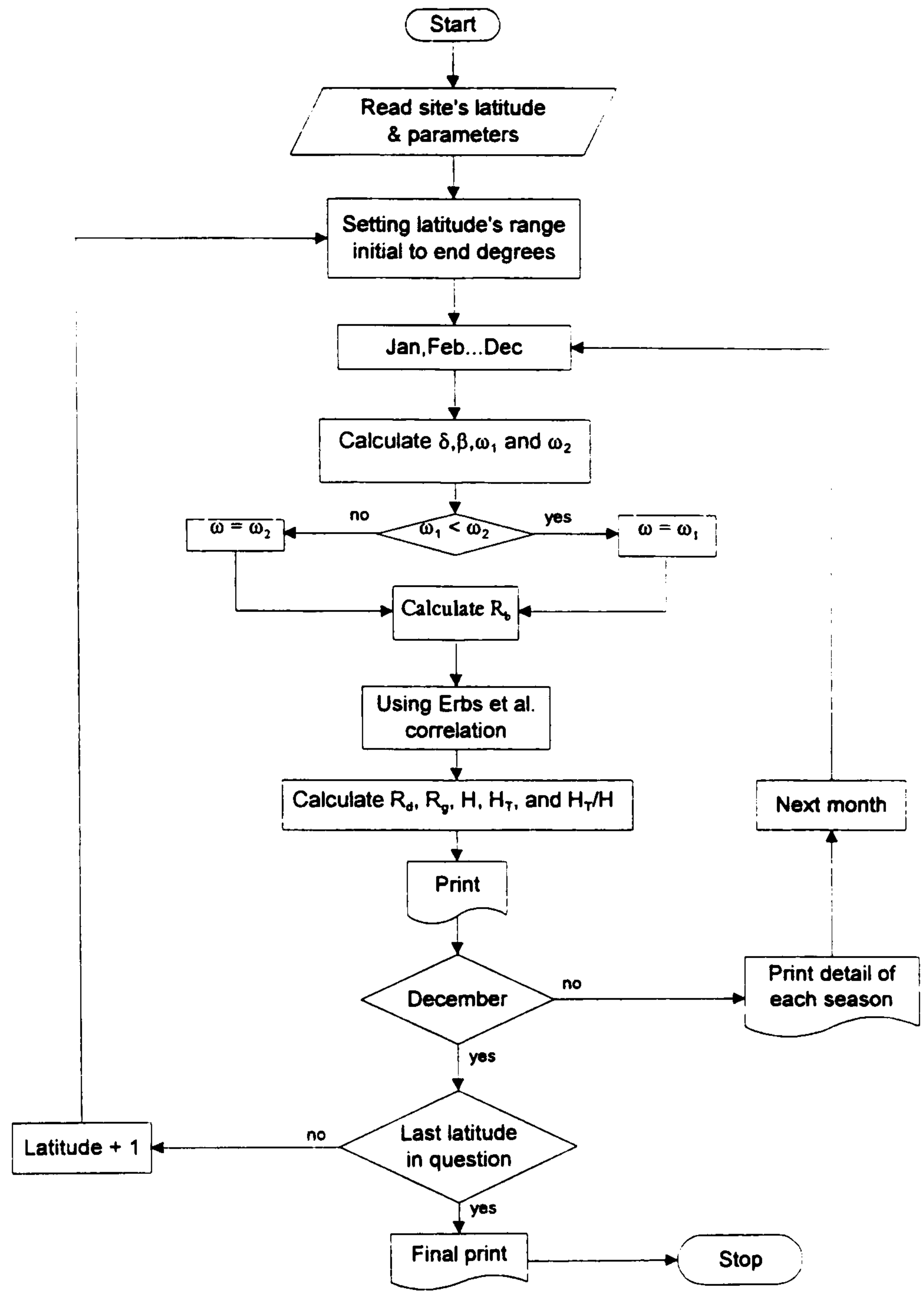


Figure B2 Flow diagram of monthly mean daily solar radiation on inclined surface

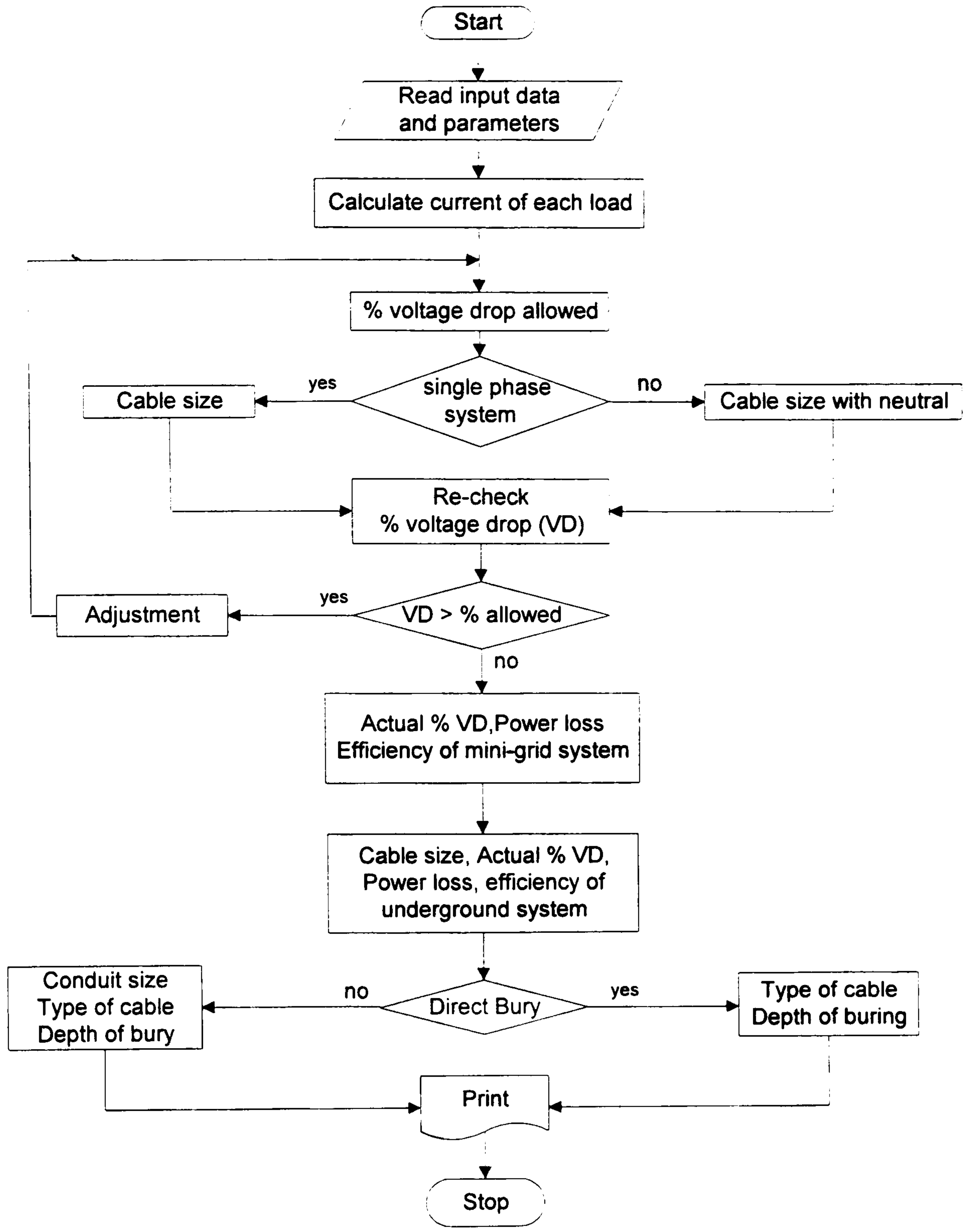


Figure B3 Flow diagram of calculation of electrical power distribution system

Appendix C

Solar Array Support Structures

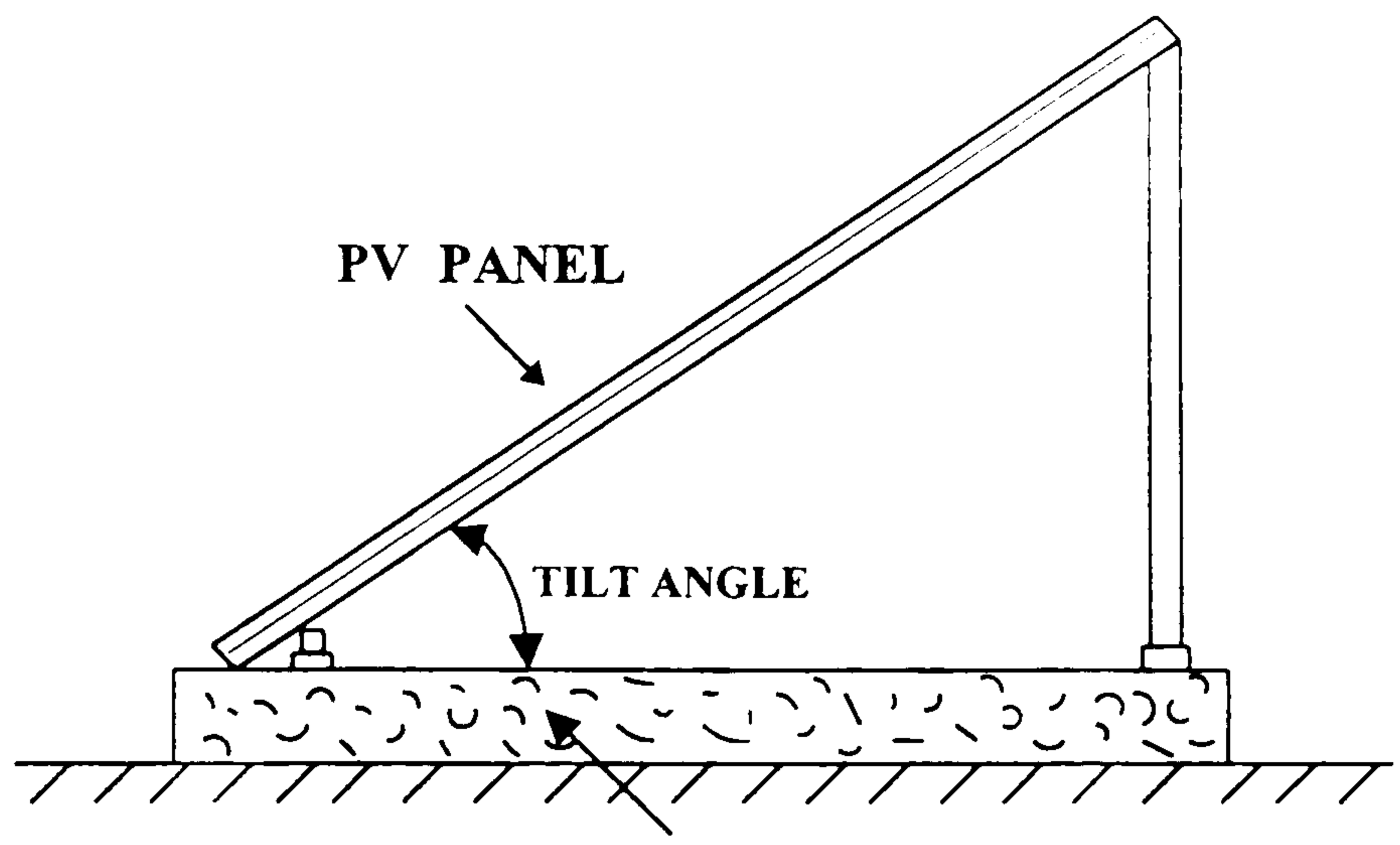


Figure C1 Racks on concrete slab

Advantages:

- Minimum earthwork is necessary for foundation.
- Road laying type of construction or present slabs reduce the cost of foundations.
- Field fabrication and erection of above ground components is minimized.
- In-service maintenance is facilitated.
- Slabs can be extended to provide a smooth running surface for equipment (automatic module surface washing surface washing machine, straddle type of maintenance vehicles, etc.).
- Above ground structural members can be of steel, aluminum or timber and can be spaced to support individual panels or sets of panels.
- Concert mat with low bearing pressures eliminates relative settlement of supports.

Disadvantages:

- In-situ testing may be required to insure adequate factor of safety against lateral sliding.
- Reinforcing steel is required in the slab for temperature and support loads.
- Site drainage is limited to ditches parallel to the arrays.

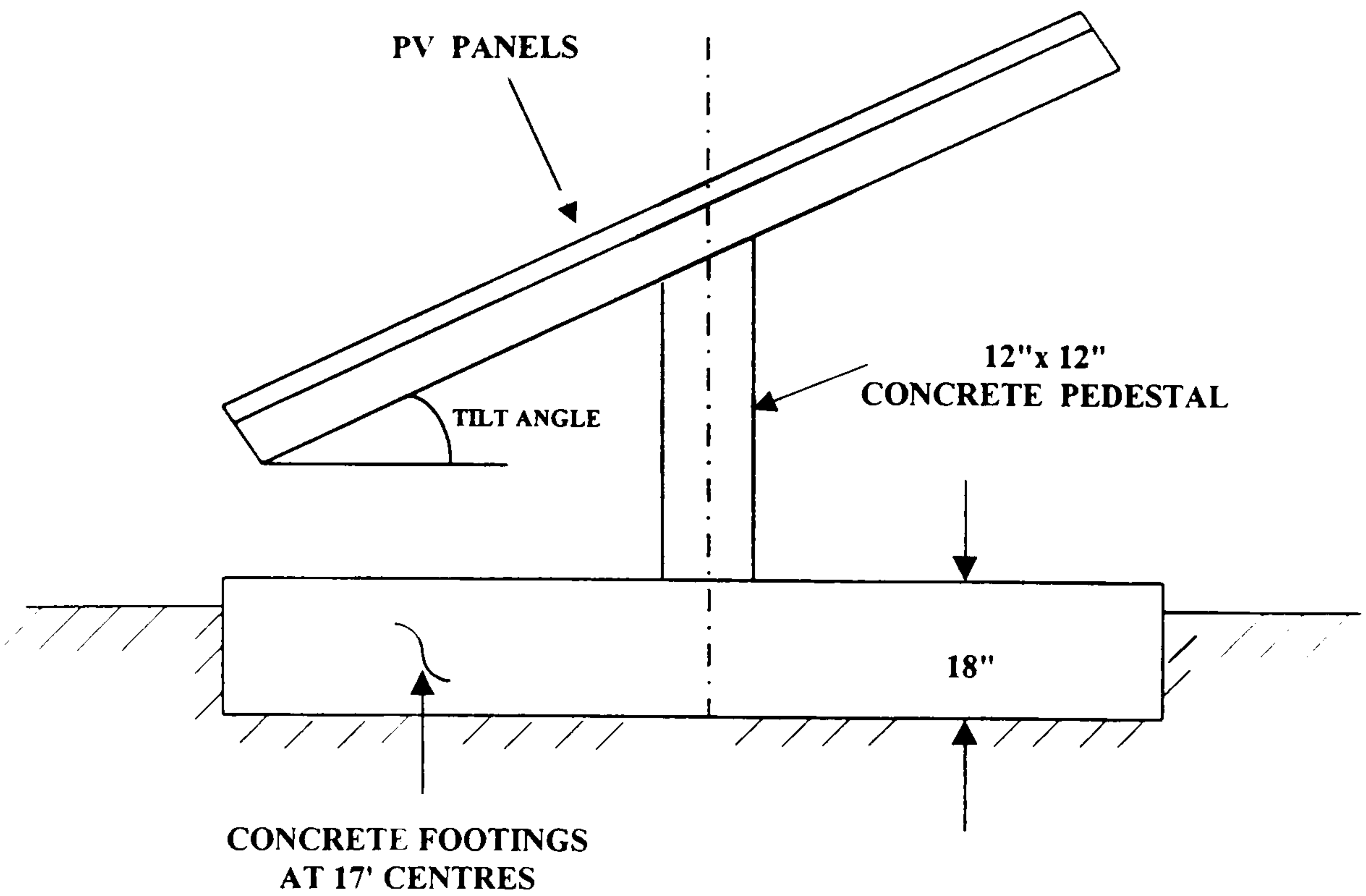


Figure C2 Racks on pedestals on footing

Advantages:

- All components can be prefabricated and shipped to the site with only field erection.
- In-service maintenance to structures will be eliminated by the use of reinforced concrete.
- Only two connections are needed between panels and supporting structures.

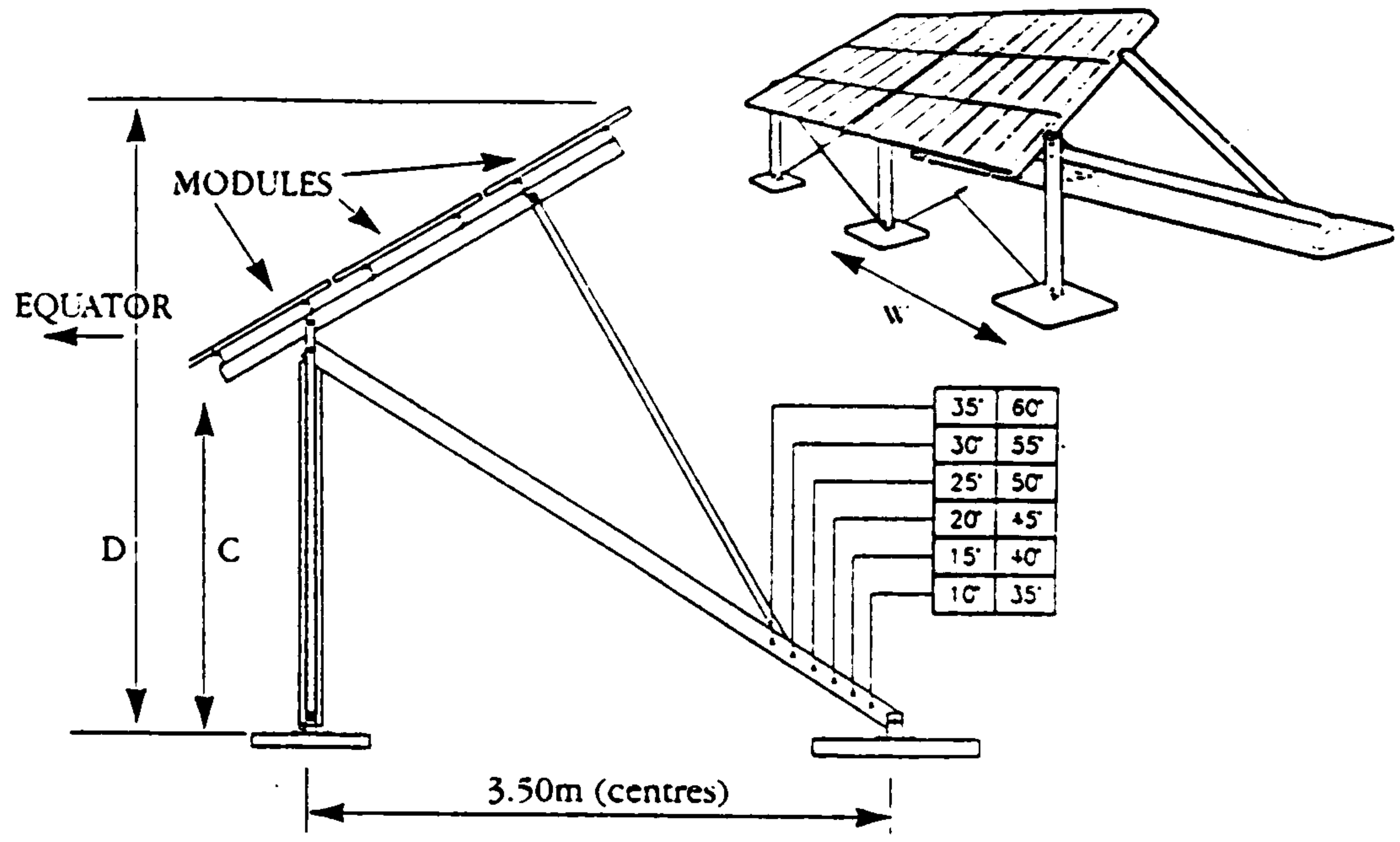
Disadvantages:

- Reinforcing steel is required in the prefabricated structures.
- Relatively large concrete structures will have to be transported and accurately placed at the site.

BP H SOLAR ARRAY SUPPORT STRUCTURE

STRUCTURE TYPE	MODULES PER STRUCTURE	STRUCTURE WIDTH (W) BP585/275 (m)
H24	24	4.48
H21	21	3.95
H18	18	3.41
H15	15	2.87
H12	12	2.33

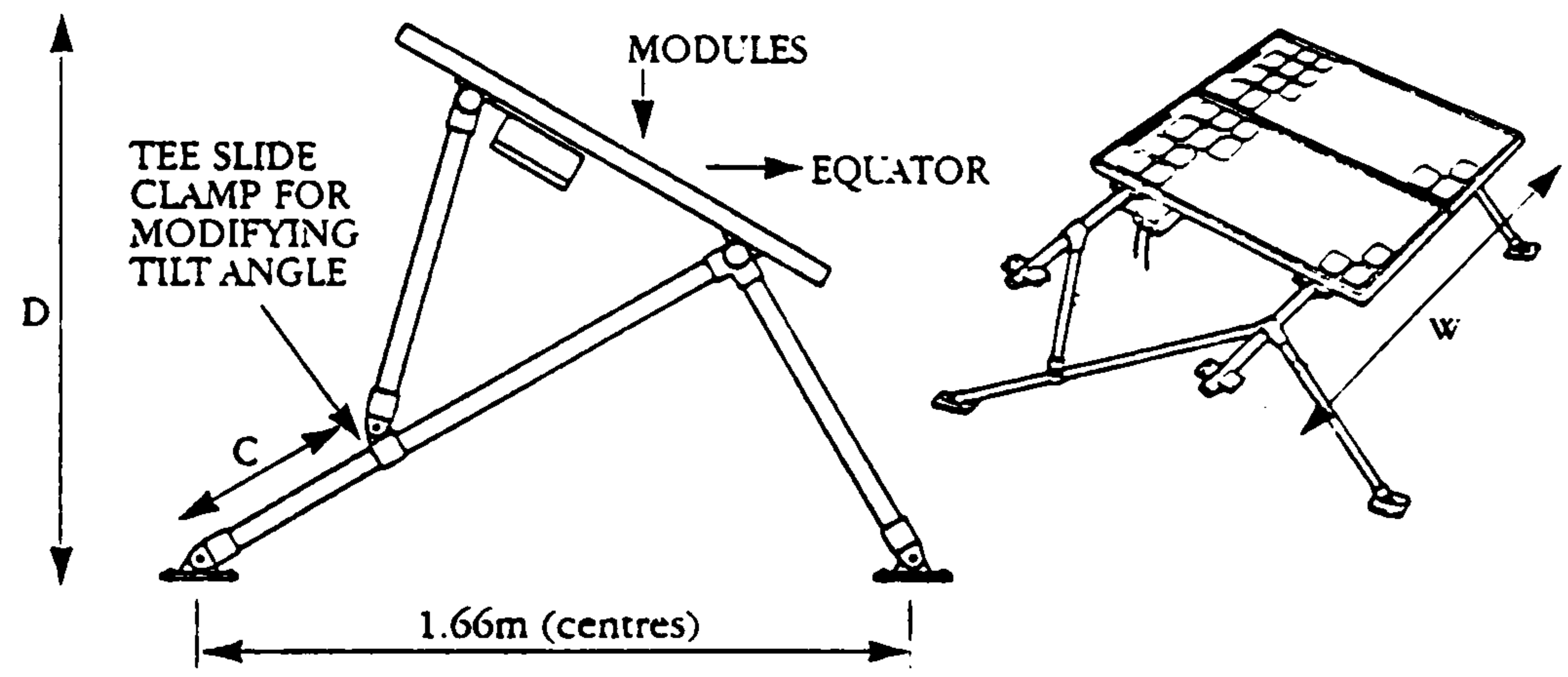
These galvanised steel structures support photovoltaic modules above the ground at the optimum tilt angle determined by site location. They consists of a kit of components that can be readily handled and assembled on site. These structures are designed to withstand adverse environmental conditions with minimal maintenance and can be coupled together to make up an array of any number of modules.



H STRUCTURES - METRES	TILT ANGLES										
	60°	55°	50°	45°	40°	35°	30°	25°	20°	15°	10°
C - BP275	1.54	1.60	1.67	1.74	1.82	1.90	1.98	2.07	2.16	2.25	2.35
D - BP275	4.71	4.60	4.48	4.34	4.19	4.02	3.84	3.65	3.44	3.24	3.02

BP T SOLAR ARRAY SUPPORT STRUCTURE

STRUCTURE TYPE	MODULES PER STRUCTURE	STRUCTURE WIDTH (W) BP585/275 (m)
T8	8	4.37
T7	7	3.82
T6	6	3.32
T5	5	2.74
T4	4	2.22
T3	3	1.68
T2	2	1.12



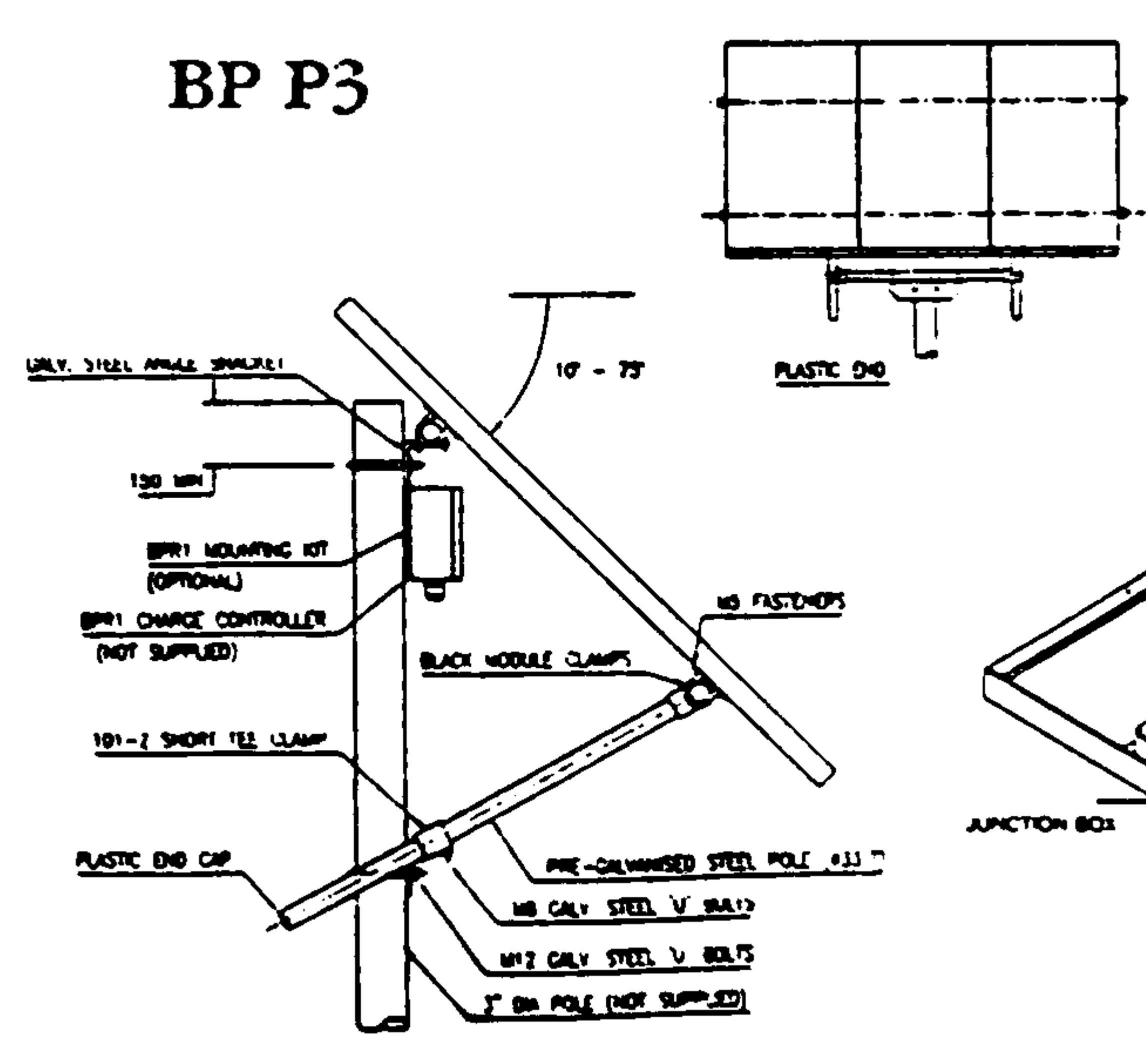
T STRUCTURES - METRES	TILT ANGLES										
	60°	55°	50°	45°	40°	35°	30°	25°	20°	15°	10°
C - BP275	.505	.520	.536	.554	.573	.593	.614	.636	.660	.682	.706
D - BP275	1.554	1.516	1.472	1.422	1.367	1.307	1.242	1.174	1.102	1.027	.950

BP P AND HV-1 SOLAR ARRAY SUPPORT STRUCTURES

STRUCTURE TYPE	BP P1	BP P2	BP P3
NO. OF MODULES	1	1 to 2	2 to 3

P Type structures are supplied for use with 3" diameter poles as standard but other sizes are available on request

BP P3



BP HV1

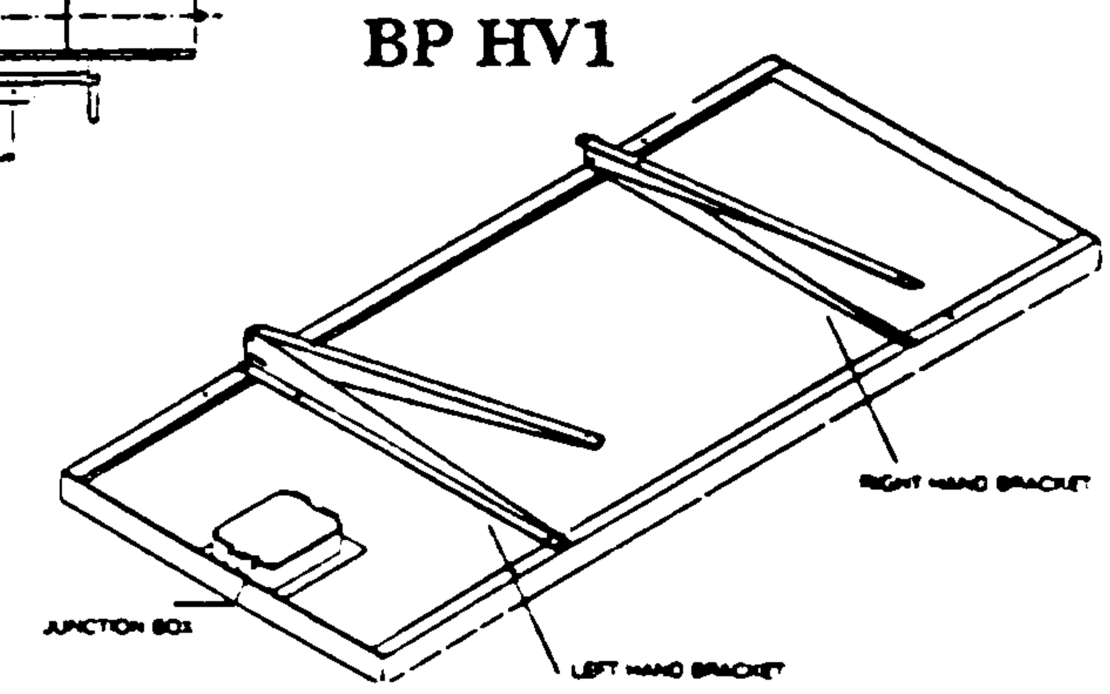


Figure C3 BP solar array support structures

Appendix D

Tables of Life Cycle Cost Analysis

Table D1 Selected values of present worth factor P_r for a cost in **n** years.

Discount Rate (**d**)	Inflation Rate (**i**)	Factor P_r for given number of years				
		5	10	15	20	30
0.00	0.00	1.00	1.00	1.00	1.00	1.00
	0.05	1.28	1.63	2.08	2.65	4.32
	0.10	1.61	2.59	4.18	6.73	17.45
	0.15	2.01	4.05	8.14	16.37	66.21
	0.20	2.49	6.19	15.41	38.34	237.38
0.05	0.00	0.78	0.61	0.48	0.38	0.23
	0.05	1.00	1.00	1.00	1.00	1.00
	0.10	1.26	1.59	2.01	2.54	4.04
	0.15	1.58	2.48	3.91	6.17	15.32
	0.20	1.95	3.80	7.41	14.45	54.92
0.10	0.00	0.62	0.39	0.24	0.15	0.06
	0.05	0.79	0.63	0.50	0.39	0.25
	0.10	1.00	1.00	1.00	1.00	1.00
	0.15	1.25	1.56	1.95	2.43	3.79
	0.20	1.55	2.39	3.69	5.70	13.60
0.15	0.00	0.50	0.25	0.12	0.06	0.02
	0.05	0.63	0.40	0.26	0.16	0.07
	0.10	0.80	0.64	0.51	0.41	0.26
	0.15	1.00	1.00	1.00	1.00	1.00
	0.20	1.24	1.53	1.89	2.34	3.59
0.20	0.00	0.40	0.16	0.06	0.03	0.00
	0.05	0.51	0.26	0.13	0.07	0.02
	0.10	0.65	0.42	0.27	0.18	0.07
	0.15	0.81	0.65	0.53	0.43	0.28
	0.20	1.00	1.00	1.00	1.00	1.00

Table D2 Selected values of present worth factor P_a for an annually recurring cost.

Discount Rate (**d**)	Inflation Rate (**i**)	Factor P_a for given number of years				
		5	10	15	20	30
0.00	0.00	5.00	10.00	15.00	20.00	30.00
	0.05	5.80	13.21	22.66	34.72	69.76
	0.10	6.72	17.53	34.95	63.00	180.94
	0.15	7.75	23.35	54.72	117.81	499.96
	0.20	8.93	31.15	86.44	224.03	1418.26
0.05	0.00	4.33	7.72	10.38	12.46	15.37
	0.05	5.00	10.00	15.00	20.00	30.00
	0.10	5.76	13.03	22.21	33.78	66.82
	0.15	6.62	17.06	33.51	59.44	164.68
	0.20	7.60	22.41	51.29	107.59	431.39
0.10	0.00	3.79	6.14	7.61	8.51	9.43
	0.05	4.36	7.81	10.55	12.72	15.80
	0.10	5.00	10.00	15.00	20.00	30.00
	0.15	5.72	12.87	21.80	32.95	64.27
	0.20	6.54	16.65	32.26	56.38	151.24
0.15	0.00	3.35	5.02	5.85	6.26	6.57
	0.05	3.83	6.27	7.82	8.80	9.81
	0.10	4.38	7.90	10.71	12.96	16.20
	0.15	5.00	10.00	15.00	20.00	30.00
	0.20	5.69	12.73	21.44	32.22	62.04
0.20	0.00	2.99	4.19	4.68	4.87	4.98
	0.05	3.41	5.16	6.06	6.52	6.87
	0.10	3.88	6.39	8.02	9.07	10.19
	0.15	4.41	7.97	10.85	13.18	16.58
	0.20	5.00	10.00	15.00	20.00	30.00

Table D3 Multipliers (C_r) to reduce a single future expense **n** years from the present worth value using a discount rate of **d**

	Real discount rate (d)																	
n	**0.01**	**0.02**	**0.03**	**0.04**	**0.05**	**0.06**	**0.07**	**0.08**	**0.09**	**0.10**	**0.11**	**0.12**	**0.13**	**0.14**	**0.15**	**0.16**	**0.17**	**0.18**
1	0.990	0.980	0.971	0.961	0.952	0.943	0.935	0.926	0.917	0.909	0.901	0.892	0.885	0.877	0.870	0.862	0.855	0.847
2	0.980	0.961	0.943	0.924	0.907	0.890	0.873	0.857	0.842	0.826	0.812	0.797	0.783	0.769	0.756	0.743	0.731	0.718
3	0.971	0.942	0.915	0.889	0.864	0.839	0.816	0.794	0.772	0.751	0.731	0.711	0.693	0.675	0.658	0.640	0.624	0.608
4	0.961	0.923	0.888	0.855	0.823	0.792	0.763	0.735	0.708	0.683	0.659	0.635	0.613	0.592	0.572	0.552	0.534	0.515
5	0.951	0.905	0.863	0.822	0.784	0.747	0.713	0.680	0.650	0.621	0.593	0.567	0.543	0.519	0.497	0.476	0.456	0.437
6	0.942	0.888	0.837	0.790	0.746	0.705	0.666	0.630	0.596	0.564	0.535	0.506	0.480	0.455	0.432	0.410	0.390	0.370
7	0.933	0.875	0.813	0.760	0.711	0.665	0.623	0.583	0.547	0.513	0.482	0.452	0.425	0.399	0.376	0.353	0.333	0.314
8	0.923	0.853	0.789	0.730	0.677	0.627	0.582	0.540	0.502	0.466	0.434	0.403	0.376	0.350	0.327	0.305	0.285	0.266
9	0.914	0.836	0.766	0.702	0.645	0.592	0.544	0.500	0.460	0.424	0.391	0.360	0.333	0.307	0.284	0.262	0.243	0.209
10	0.905	0.820	0.744	0.675	0.614	0.558	0.508	0.463	0.422	0.358	0.352	0.321	0.295	0.269	0.247	0.226	0.206	0.191
11	0.896	0.804	0.722	0.649	0.585	0.526	0.475	0.428	0.388	0.350	0.317	0.287	0.261	0.236	0.215	0.195	0.178	0.162
12	0.887	0.788	0.701	0.624	0.557	0.497	0.444	0.397	0.356	0.318	0.286	0.256	0.231	0.207	0.187	0.168	0.152	0.137
13	0.879	0.773	0.681	0.601	0.530	0.468	0.415	0.367	0.326	0.289	0.258	0.229	0.204	0.182	0.163	0.145	0.130	0.116
14	0.87	0.758	0.661	0.577	0.505	0.442	0.388	0.340	0.299	0.263	0.232	0.204	0.181	0.159	0.141	0.125	0.111	0.098
15	0.861	0.743	0.642	0.555	0.481	0.417	0.362	0.315	0.275	0.239	0.209	0.182	0.160	0.140	0.123	0.108	0.095	0.083
16	0.853	0.728	0.623	0.534	0.458	0.393	0.339	0.291	0.252	0.217	0.188	0.163	0.141	0.122	0.107	0.093	0.061	0.070
17	0.844	0.714	0.605	0.513	0.436	0.371	0.317	0.270	0.231	0.197	0.170	0.145	0.125	0.122	0.093	0.080	0.069	0.060
18	0.836	0.700	0.587	0.493	0.416	0.350	0.296	0.250	0.212	0.179	0.153	0.130	0.111	0.107	0.080	0.069	0.059	0.050
19	0.828	0.686	0.570	0.474	0.396	0.330	0.277	0.231	0.194	0.163	0.138	0.116	0.098	0.094	0.070	0.059	0.051	0.043
20	0.820	0.673	0.554	0.456	0.377	0.311	0.258	0.214	0.178	0.148	0.124	0.103	0.087	0.072	0.061	0.051	0.043	0.036

Table D4 Multipliers (C_a) to reduce a regular annual expense over **n** years to present value using a discount rate of **d**

n	Real discount rate (d)																	
	0.01	**0.02**	**0.03**	**0.04**	**0.05**	**0.06**	**0.07**	**0.08**	**0.09**	**0.10**	**0.11**	**0.12**	**0.13**	**0.14**	**0.15**	**0.16**	**0.17**	**0.18**
1	0.990	0.980	0.971	0.961	0.952	0.943	0.935	0.926	0.917	0.909	0.901	0.892	0.885	0.877	0.870	0.862	0.855	0.847
2	1.970	1.941	1.913	1.886	1.859	1.833	1.808	1.783	1.759	1.735	1.713	1.690	1.668	1.646	1.626	1.606	1.585	1.566
3	2.941	2.884	2.829	2.775	2.723	2.673	2.624	2.577	2.531	2.486	2.444	2.401	2.361	2.321	2.283	2.246	2.210	2.174
4	3.902	3.807	3.717	3.629	3.546	3.465	3.387	3.312	3.240	3.170	3.102	3.037	2.974	2.913	2.855	2.799	2.743	2.690
5	4.853	4.713	4.580	4.451	4.329	4.212	4.100	3.992	3.890	3.790	3.696	3.604	3.517	3.433	3.352	3.275	3.199	3.127
6	5.795	5.601	5.417	5.242	5.076	4.917	4.767	4.623	4.486	4.355	4.231	4.111	3.998	3.888	3.784	3.685	3.589	3.498
7	6.728	6.472	6.230	6.002	5.786	5.582	5.389	5.206	5.033	4.868	4.712	4.563	4.423	4.288	4.160	4.039	3.922	3.812
8	7.652	7.325	7.020	6.732	6.463	6.209	5.971	5.746	5.535	5.335	5.146	4.967	4.799	4.638	4.487	4.344	4.207	4.078
9	8.566	8.162	7.786	7.435	7.106	6.801	6.515	6.247	5.995	5.759	5.537	5.328	5.132	4.946	4.772	4.607	4.451	4.303
10	9.471	8.982	8.530	8.110	7.722	7.360	7.024	6.710	6.418	6.144	5.889	5.650	5.426	5.216	5.019	4.834	4.659	4.494
11	10.36	9.786	9.253	8.760	8.306	7.886	7.499	7.139	6.805	6.495	6.207	5.937	5.687	5.453	5.234	5.029	4.836	4.656
12	11.25	10.57	9.954	9.385	8.863	8.383	7.943	7.536	7.161	6.813	6.492	6.194	5.918	5.660	5.421	5.197	4.988	4.793
13	12.13	11.34	10.63	9.985	9.394	8.852	8.358	7.903	7.487	7.103	6.750	6.423	6.122	5.842	5.583	5.342	5.118	4.909
14	13.00	12.10	11.29	10.56	9.899	9.295	8.745	8.244	7.786	7.366	6.982	6.628	6.302	6.002	5.724	5.468	5.229	5.008
15	13.86	12.85	11.93	11.11	10.38	9.712	9.108	8.559	8.061	7.606	7.191	6.810	6.462	6.142	5.847	5.576	5.324	5.091
16	14.71	13.57	12.56	11.65	10.84	10.10	9.447	8.851	8.313	7.823	7.379	6.974	6.604	6.263	5.954	5.668	5.405	5.162
17	15.56	14.29	13.16	12.16	11.27	10.47	9.763	9.121	8.544	8.021	7.549	7.119	6.729	6.373	6.047	5.749	5.475	5.222
18	16.39	14.99	13.75	12.66	11.69	10.82	10.06	9.371	8.756	8.201	7.702	7.249	6.840	6.467	6.128	5.818	5.534	5.273
19	17.22	15.67	14.32	13.13	12.08	11.15	10.33	9.603	8.950	8.365	7.839	7.366	6.938	6.550	6.198	5.877	5.584	5.316
20	18.04	16.35	14.87	13.59	12.46	11.47	10.69	9.818	9.129	8.513	7.963	7.469	7.025	6.623	6.259	5.928	5.628	5.352

Appendix E

Instruction for the Design Worksheets

There are a number of terms mentioned in each block of the blank worksheets. An instruction of the following terms should be able to help users to easily complete on the worksheets.

AC power (W) : Enter the voltage of the load in watts. Some manufacturers include the power rating for the unit. Use the manufacturer's rating or calculate the value as shown on the worksheet.

Allowable voltage drop (decimal) : Enter the maximum 'allowable percentage voltage drop' for each of the wire runs. The NEC recommends a maximum of 3% voltage drop in array branch circuit and a maximum of 5% voltage drop from source to load.

Ampere-hours load (Ah/day): The average energy required per day in ampere-hours.

Array rating estimated (W_P) : The peak power from calculation in peak watts.

Array sizing installed (W_P) : The peak power can be produced from the PV array installed at Normal Standard Test Condition (NSTC).

Battery efficiency (decimal) : This factor accounts for the losses due to the battery storage subsystem. Use data from manufacturer on a specific battery (if available).

Corrected ampere-hours (Ah/day) : The energy required to meet the average daily load. This is the load that the PV system must meet.

Corrected array current (A) : The current that the PV array will need to produce to meet the loads.

Corrected battery capacity (Ah) : The calculated battery capacity necessary to meet the daily load for the required number of days.

Daily duty cycle (h/day) : The average amount of time per day the load will be used. (Enter fraction of hours in decimal form, i.e., 1 hours-15 minutes would be entered as 1.25).

Day of autonomy (days) : The consecutive number of days the battery subsystem is required to meet the daily ampere-hours load with no energy production by the PV array.

DC or AC : Type of loads to be used that can be found from the load voltage named on the name plate or manufacturer's technical data.

DC power (W) : Enter the rated power required for the DC load in watts. Use the manufacturer's rating or calculate the value as shown on the worksheet.

Design controller capacity (A) : Calculate the design controller capacity used.

Drawdown level (m) : The vertical distance measured from the static water level to the water level when the source is being pumped. This value is often determined by test pumping when the source is developed. If no information is available, an estimate of 10% of static water level can be used.

Each battery capacity (Ah) : Manufacturer's rating of storage capacity in ampere-hours. Batteries are normally rated at optimum test conditions with constant temperature and discharge rate.

Each rated ampere of controller (A) : Enter the rated current of the controller selected for design in ampere. Use the manufacturer's data.

Electrical energy (Wh/day) : The energy that the PV array must provide to the pumping system to meet average water requirements.

Friction loss (decimal) : The pressure caused by friction in the pipe and delivery system expressed as a percent of the static head. If no information is available, about 5% of the static head can be used.

Hydraulic energy (Wh/day) : The energy required to lift the daily water demand to the total pumping head expressed in watt-hours/day.

Hydraulic power (W) : The power required to lift the daily water demand to the total pumping head expressed in watts.

Line loss factor (decimal) : The decimal fraction for energy loss due to wiring. This factor can vary from 0.95-0.98.

Load current (A) : Enter the manufacturer's rated current (label or name plate) in amperes. Other sources are actual measurement or experience.

Load description : Briefly describe of each load (i.e., fluorescent lamp, radio, TV, refrigerator and motor/pump). Enter one load per line.

Load voltage (V) : Enter the voltage of the load in volts. Measure or consult with the manufacturer.

Maximum current of a PV module (A) : Enter the maximum rated current of the single module used at NSTC.

Max. depth of discharge (decimal) : The maximum discharge allowed by designer for the battery subsystem. Use of the battery manufacturer's data is recommended.

Maximum voltage of a PV module (V) : Enter the maximum rated voltage of the single module used at NSTC.

Module degradation factor (decimal) : A factor that adjusts module current from standard test conditions to normal operating conditions (i.e., higher temperatures, dust, mismatch loss degradation over time). Use the manufacturer, technical data.

Motor/pump efficiency (decimal) : Enter the average efficiency of the motor/pump used. Using the manufacturer's technical data is recommended.

No. of batteries connected in parallel : The number of parallel connected batteries necessary to provide the proper system current.

No. of batteries connected in series : The number of series connected batteries necessary to provide the proper system voltage.

No. of controllers in parallel : Calculate the number of parallel controllers needed.

No. of days battery used (days) : Enter the number of days of battery used on daily energy need basis, before bring a battery is being used to a station for charging.

No. of modules connected in parallel : The number of parallel modules (strings) required to produce the system current.

No. of modules connected in series : The number of series modules in a string required to produce the system voltage.

No. of sets : Enter the quantity of identical loads in the system to be used.

Nominal battery voltage (V) : Rated battery voltage of the selected battery to be used in the system.

Nominal system voltage (V) : System voltage is the nominal voltage of the battery storage. Common values are 12,24,48 and 120 volts.

Nominal voltage of a PV module (V) : Most modules have a peak power voltage at about 15-17 volts, their nominal voltage is about 12 volts. Almost all modules used in PV system are 12 volts.

Peak sun (h/day) : Enter the average number of hours each day when insolation was 1000 W/m^2. Find the corresponding solar irradiation ($Wh/m^2/day$), and divided by 1000 W/m^2 to obtain the number of possible peak sun hours in a day.

Peak sun hours at selected tilt angle (h/day) : This is the same value of peak sun that was selected from the worksheet #2.

Peak power of a PV module used (W_P) : Enter the peak power of the single module used at NSTC.

Power conversion eff. (decimal) : A sizing correction factor accounting for power loss in systems using power conditioning components (inverter, ballast or converter).

Power factor (decimal) : The average value of power factor of load in AC circuit during operation.

Rated current of a PV module (A) : Rated current of module at NSTC.

Rated current of protective device (A) : Rated current of fuse, circuit breaker (CB), switch or surge devices that are selected for use in the system.

Rated load current (A) : Enter the total current flows through the specific (branch) circuit in question expressed in amperes.

Regulator efficiency (decimal) : This factor accounts for the losses due to the electronic controller such as charge regulator.

Short circuit current of a module (A) : Enter the rated short circuit current's a module used at NSTC.

Source water capacity (litres/hour) : The long term water yield that the source is capable of supplying. Capacity is expressed in litres/hours.

Static head level (m) : The total vertical distance that the water is to be lifted above the water level without considering friction.

Static lift level (m) : Total vertical distance that the water will be lifted above ground level to the point of discharge (water tank).

Static water level (m) : The vertical distance measured in metres from the ground level to the water level in the source when no water is being pumped.

Total AC load power (W) : Enter this value from worksheet # 1.

Total DC load power (W) : Enter this value from worksheet # 1.

Total No. of batteries used : The total number of batteries installed in the system.

Total No. of modules used : The total number of modules installed in the system.

Total pumping head (m) : The total of all lifts and pressures corrected for friction expressed in metres of water.

Total pumping subsystem efficiency (decimal) : The total of an average daily efficiency that the pumping system will achieve. This value affects system size.

Total short circuit current (A) : The total value of the short circuit current of the PV array.

Volume-head product (m^4/day) : This is simply the volume per day multiplied by the total head.

Water volume required (m^3/day) : The average daily water needed to meet the users demand. If this value varies on a monthly basis, choose the month that has a highest ratio of water demand-to-solar insolation and use that month as the design month.

Weekly duty cycle (d/week) : The number of days each week that loads will be used.

Instruction for sequential choosing of these worksheets to design a decentralised PV specific system

worksheet #	battery charging station	water pumping system	refrigerator and freezer system	public lighting system	community facilities system	solar home system
general consideration	*	*	*	*	*	*
1	*		*	*	*	*
2	*	*	*	*	*	*
BCS	*					
1WP		*				
2WP		*				
3WP		*				
RS			*			
PLS				*		
CCS					*	
SHS						*
CC	*		*	*	*	*
PC		*			*	
PSC	*	*	*	*	*	*
ACW		*			*	
DCW	*		*	*	*	*
LLC	*	*	*	*	*	*

GENERAL CONSIDERATION
Application : **Site :** **Location :** **Environment :** **Maximum Wind Speed :** **Load :**
ARRAY :
CONTROLLER :
BATTERIES :
INVERTER :
LOAD :
WIRING/SWITCH GEAR :
MOUNTING :

Worksheet #1	Calculation of the daily load demand											
Load description	DC or AC	No. of sets	Load current (A)	Load voltage (V)	DC power (W)	AC power (W)	Daily duty cycle (h/day)	Weekly duty cycle (d/week)	7 days in a week	Power conversion eff. (decimal)	Energy requirement (Wh/day)	Nominal system voltage (V)	Ampere hour load (Ah/day)
			×	×	=	=	×	×	÷	×	=	÷	=
									7				
									7				
									7				
									7				
									7				
									7				
									7				
									7				
									7				
Total DC load power (W)							Total AC load power (W)			Total Wh/day		Total Ah/day	

Design Notes :

Maximum Tilt Angle Worksheet # 2	**Estimate The Maximum Tilt Angle (case study of Thialnd)**

Site : **Latitude :** **Longitude :**

Tilt at latitude - 25°

Month	Ampere-hours load (Ah/day)		Peak sun (h/day)		Current (A)	Select the largest current and corresponding peak sun	
Jan.		÷		=			
Feb.		÷		=			
Mar.		÷		=			
Apr.		÷		=			
May		÷		=		latitude - 25°	
Jun.		÷		=		peak sun (h/day)	current (A)
Jul.		÷		=			
Aug.		÷		=			
Sep.		÷		=			
Oct.		÷		=			
Nov.		÷		=			
Dec.		÷		=			

Tilt at latitude

Month							
Jan.		÷		=			
Feb.		÷		=			
Mar.		÷		=			
Apr.		÷		=			
May		÷		=		latitude	
Jun.		÷		=		peak sun (h/day)	current (A)
Jul.		÷		=			
Aug.		÷		=			
Sep.		÷		=			
Oct.		÷		=			
Nov.		÷		=			
Dec.		÷		=			

Tilt at latitude + 25°

Month							
Jan.		÷		=			
Feb.		÷		=			
Mar.		÷		=			
Apr.		÷		=			
May		÷		=		latitude + 25°	
Jun.		÷		=		peak sun (h/day)	current (A)
Jul.		÷		=			
Aug.		÷		=			
Sep.		÷		=			
Oct.		÷		=			
Nov.		÷		=			
Dec.		÷		=			

	peak sun (h/day)	current (A)
Now select the latitude angle that give the smallest current and corresponding peak sun from each latitude and enter on the right hand side		
	Max. tilt angle selected	
Note : This angle is for fixed tilt angle throughout the year		

Design Notes:

Charge Controller General Worksheet # CC	**Technical Specifications of Charge Controller**								
Short circuit current of a module (A)	No. of modules in parallel		Safety factor		Design controller capacity (A)		Each rated ampere of controller (A)		No. of controllers in parallel
	×		×	1.25	=		÷		=

Manufacturer : Regulator Type : System voltage (V) : Maximum load current (A) : Operating temperature (˚C) : Fuse rating (A) : Disconnection pre-warning : Disconnection level : Reconnection level : ***Metering and protection*** Voltage : ✓❑ Yes ❑ No Current : ✓❑ Yes ❑ No State of Charge (SOC) : ✓❑ Yes ❑ No Under and Overvoltage : ✓❑ Yes ❑ No Over-temperature, load current : ✓❑ Yes ❑ No Others : LED display for charge control and over-discharge protection	**Design Notes :**

Power Conditioning General Sheet # PC	**Power Conditioning Unit Specification Sheet**						
Total AC power load (W)	Power conversion efficiency (decimal)		Safety factor		Minimum inverter size wattage (W)		Round up to next inverter size (W)
	÷		×	1.25	=		

Inverter

Manufacture : Inverter model no. : Output waveform : Nominal input voltage (VDC) : Output voltage (VAC) : Frequency regulation (H_Z) : Nominal power (W) : Maximum AC load current (A) : Efficiency (%) :	**Design Notes :**

Converter

System Requirement		
Input DC voltage :	VDC	
Output DC voltage :	VDC	
Output power :	W	
Converter Designed		
Manufacturer :		
Model :		
Input voltage :	VDC	
Output voltage :	VDC	
Output current :	A	

Protection of System Components General Worksheet # PSC	Protection of System Components

Array Description								
Array short circuit current (A)	No. of modules connected in parallel		Total array short circuit current (A)		Safety factor		Rated current of protective device (A)	
	×		=		×	1.25	=	

Controller / Main Load Description								
Total DC load power (W)	Nominal system voltage (V)		Maximum DC load current (A)		Safety factor		Rated current of protective device (A)	
	÷		=		×	1.25	=	

Battery Description								
Maximum current of a module (A)	No. of modules connected in parallel		Peak current from PV array (A)		Safety factor		Rated current of protective device (A)	
	×		=		×	1.25	=	

Inverter Description								
Total AC load power (W)	Nominal system voltage (V)		Power factor (decimal)		Safety factor		Rated current of protective device (A)	
	÷		÷		×	1.25	=	

Branch Circuit # 1 (specify)					Branch Circuit # 2 (specify)				
Rated load current (A)	Safety factor		Rated current of protective device (A)		Rated load current (A)	Safety factor		Rated current of protective device (A)	
	×		=			×	1.25	=	
Branch Circuit # 3 (specify)					Branch Circuit # 4 (specify)				
Rated load current (A)	Safety factor		Rated current of protective device (A)		Rated load current (A)	Safety factor		Rated current of protective device (A)	
	×		=			×	1.25	=	

Circuit	Protective Device (No. of Devices)				Rated Current	Rated Voltage	Descriptions
	CB	Fuse	Switch	Surge	(A)	(V)	

Design Notes:

AC wiring General Worksheet # ACW	AC Wire Sizing Specification				
Description	System voltage (V)	Maximum current (A)	Allowable voltage drop (%)	Wire size (mm^2)	Wire type
AC Circuit					
Inverter to AC load					
AC Power Distribution line					
Branch Circuit					
1.					
2.					
3.					
4.					
5.					
System Grounding	Wire Size (mm^2)		Wire Type		Type of Earth Ground
Equipment Ground					
system					
Design Notes:					

DC Wring General Worksheet # DCW	DC Wire Sizing Specification				
Descriptions	System voltage (V)	Maximum current (A)	Allowable voltage drop (%)	Wire size (mm^2)	Wire type
Array Circuit					
Module to Module					
Array to Control Building					
Array to Controller					
DC Circuits					
Battery to Battery					
Battery Charger to Battery					
Battery to Inverter or Converter					
Regulator to DC load					
Branch Circuit					
1.					
2.					
3.					
4.					
5.					
System Grounding	Wire Size (mm^2)		Wire Type		Type of Earth Ground
Equipment Ground					
System					
Design Notes:					

Battery Charging Station Worksheet # BCS	PV System Sizing of Battery Charging Station
Site : Array tilt angle : Degrees Monthly mean daily solar radiation : kWh/m^2	The worst month of the year : Number of charging points required : Availability required :

1) PV Array Sizing

Ampere-hours load (Ah/day)		Regulator efficiency (decimal)		Battery efficiency (decimal)		Line loss factor (decimal)		Corrected ampere-hours (Ah day)
	÷		÷		÷		=	

Corrected ampere-hours (Ah/day)		Peak sun hours at selected tilt angle (h/day)		Module degradation factor (decimal)		No. of days battery used (days)		Corrected array current (A)
	÷		÷		×		=	
						Rated current of a PV module (A)	÷	
						No. of modules connected in parallel	=	

Nominal system voltage (V)		Nominal voltage of a PV module (V)		No. of modules connected in series		No. of modules connected in parallel		Total number of modules used per point
	÷		=		×		=	
						Number of charging points required	×	
						Total number of modules used	=	

2) Battery Sizing

Corrected ampere-hours (Ah/day)		Days of battery used (day)		Max. depth of discharge (decimal)		Corrected battery capacity (Ah)		Each battery capacity (Ah)		No. of batteries connected in parallel
	×		÷		=		÷		=	

Nominal system voltage (V)		Nominal battery voltage (V)		No. of batteries connected in series		No. of batteries connected in parallel		Total number of batteries used
	÷		=		×		=	

PV module information		Battery information
Manufacturer :		Manufacturer :
Model :		Model :
Type :		Type :
SC current : A	OC voltage : V	Nominal voltage V
Max. current : A_{mp}	Max. voltage : V_{mp}	Rated capacity : Ah

Design Notes :

Water Pumping Worksheet # 1 WP	Calculation of the Water Pumping Load

Application : Site : Location :	Source water capacity : litres/hour Water volume required : m^3 day Day of autonomy : days Availability required :

1) Total Pumping Head

Static water level (m)		Drawdown level (m)		Static lift level (m)		Static head level (m)		Friction loss (decimal)		Static head level (m)		Total pumping head (m)
	+		+		=		×		+		=	

2) Hydraulic Energy

Water volume required (m^3/day)		Total pumping head (m)		Volume-head product (m^4/day)		Conversion factor		Hydraulic energy (Wh/day)
	×		=		÷	**0.367**	=	

3) Total Pumping Subsystem Efficiency

Motor/pump efficiency (decimal)		Battery efficiency (decimal)		Inverter efficiency (decimal)		Line loss factor (decimal)		Module degradation (decimal)		Total pumping subsystem efficiency (decimal)
	×		×		×		×		=	

4) Array Pumping Load

Hydraulic energy (Wh/day)		Total pumping subsystem efficiency (decimal)		Electrical energy (Wh/day)		Nominal system voltage (V)		Ampere-hours load (Ah/day)
	÷		=		÷		=	

Water Pump and Motor Information	Notes
Pump Type : Manufacturer : Motor type : Motor Model : Power : Input Voltage (AC) : Mean Pump/Motor Efficiency : %	✱ If the pumping system has no battery and/or electronic controller, then enter a value of efficiency is/are 1.0 and sheet # 2 WP in the topic 2 (battery -sizing) does not need to be completed for system without battery back up.

Design Notes :

Water Pumping Worksheet # 2 WP	**Calculation of Array Sizing Installed and Battery Sizing**

Electrical energy (Wh/day)		Peak sun hours at selected tilt angle (h/day)		Array rating estimated (W_P)		Peak power of a PV module used (W_P)		No. of modules used
	÷		=		÷		=	

1) Max. PV Array Sizing Installed

Nominal system voltage (V)		Nominal voltage of a PV module (V)		No. of modules connected in series		No. of modules used		No. of modules connected in series		No. of modules connected in parallel
	÷		=				÷		=	

No. of modules connected in parallel		Maximum current of a PV module (A)		No. of modules connected in series		Maximum voltage of a PV module (V)		Array sizing installed (W_P)
	×		×		×		=	

2) Battery Sizing

Electrical energy (Wh/day)		Nominal system voltage (V)		Corrected ampere-hour (Ah/day)		Day of autonomy (days)		Max. depth of discharge (decimal)		Corrected battery capacity (Ah)
	÷		=		×		÷		=	
								Each battery capacity (Ah)	÷	
								No. of batteries connected in parallel	=	

Nominal system voltage (V)		Nominal battery voltage (V)		No. of batteries connected in series		No. of batteries connected in parallel		Total no. of batteries used
	÷		=		×		=	

PV Module Information	**Battery Information**
Manufacturer : Model : Type : Open Circuit Voltage (V) : Short Circuit Current (A) : Peak Voltage (V_{MP}) : Peak Current (A_{MP}) : Peak Power (W_P) :	Manufacturer : Model : Type : Nominal Voltage (V) : Capacity (Ah) :

Design Notes :

Water Pumping Worksheet # 3 WP	Calculation of Peak Water Flow Rate

Array sizing installed (W_P)		Total pumping subsystem efficiency (decimal)		Hydraulic power (W)		Conversion factor		Total pumping head (m)		Peak water flow rate (litres hour)
	×		=		×	367	÷		=	

Peak water flow rate (litres/hour)	**compared with**	Source water capacity (litres/hour)	**: Notes :**

Does peak water flow rate exceed source capacity?		If peak water flow rate is grater than source water capacity, consider the following options: 1) Reduce water volume required and consider a battery storage subsystem to operate during night time or low insolation. Then, recalculate the design. 2) Develop a water resource capacity.
☐ **NO** **PV pumping system designed is suitable for operating in this case.**	☐ **YES** **See Notes**	

Design Notes:

(Specific) System Worksheet # RS or (#PLS) or (#CCS) or (#SHS)	Calculation of PV Array and Battery Sizing
Site : Daily load : Wh/day Tilt angle : Degrees Monthly mean daily solar radiation : kWh/m^2 Availability required :	Battery efficiency : % Max. DOD : % Regulator efficiency : % Line loss factor : % Nominal system voltage : VDC

1) PV Array Sizing

Ampere-hour load (Ah/day)		Regulator efficiency (decimal)		Battery efficiency (decimal)		Line loss factor (decimal)		Corrected amperes- hour (Ah/day)
	÷		÷		÷		=	

Corrected ampere-hours (Ah/day)		Peak sun hours at selected tilt angle (h/day)		Module degradation factor (decimal)		Corrected array current (A)
	÷		÷		=	
				Rated current of a PV module	÷	
				Number of modules connected in parallel	=	

Nominal system voltage (V)		Nominal voltage of a PV module (V)		No. of modules connected in series		No. of modules connected in parallel		Total number of modules used
	÷		=		×		=	

2) Battery Sizing

Corrected ampere-hour (Ah/day)		Days of autonomy (day)		Max. depth of discharge (decimal)		Corrected battery capacity (Ah)		Each battery capacity (Ah)		No. of batteries connected in parallel
	×		÷		=		÷		=	

Nominal system voltage (V)		Nominal battery voltage (V)		No. of batteries connected in series		No. of batteries connected in parallel		Total number of batteries used
	÷		=		×		=	

PV module information		**Battery information**
Manufacturer :		Manufacturer
Model :		Model :
Type :		Type
SC current : A	OC voltage : V	Nominal voltage : V
Max. current : A_{mp}	Max. voltage : V_{mp}	Capacity : Ah

Design Notes :

Worksheet # LCC Life cycle cost analysis of a PV stand-alone power system.

Project/Site :	Type of system :			
1. Financial parameters	*Symbol*	*Values*	*Unit*	*Remark*
Period of analysis	n		years	project lifetime
Discount rate	d			
Inflation rate	i			
Discount factor	a			$a = (1+I)(1-d)$
Annualised factor	$P_{a(n)}$			$P_{a(n)} = a(1-a^n)(1-a)$
2. System specification and performance				
Load				
Daily load	L_d		kWh/day	
Annual load	L_a		kWh/year	$365*L_d$
Solar Module				
Array size	S_a		W_P	
Module unit price	S_p		$\$/W_P$	
Lifetime	S_{lt}		years	
Battery				
Battery capacity	B_c		kWh	
Battery unit price	B_p		$/kWh	
Lifetime	B_{lt}		years	
Controller				
No. of controllers used	R_t			
Charge controller unit price	R_p		$	
Controller lifetime	R_{lt}		years	
Power Conditioner				
Inverter size	I_{in}		kW	
Inverter unit price	I_p		$/kW	
Lifetime	I_{lt}		years	
Mounting and Foundation				
Mounting & Foundation unit price	K_p		$\$/W_P$	
Lifetime	K_{lt}		years	
3. Cost data				
PV array	C_{pv}		$	$C_{pv} = S_a * S_p$
Battery	C_{bat}		$	$C_{bat} = B_c * B_p$
Charge controllers	C_{cc}		$	$C_{cc} = R_t * R_p$
Power conditioner	C_{pc}		$	$C_{pc} = I_{in} * I_p$
Mounting & Foundation	C_{sw}		$	$C_{sw} = S_a * K_p$
Installation (20%)	C_{in}		$	$C_{in} = 0.2*C_{pv}$
a) Capital Cost	C_{cap}		$	
Operation & Maintenance (2%)	C_{om}		$	$C_{om} = 0.02*C_{pv}$
b) Life Cycle O&M Cost	$C_{o\&m}$		$	$C_{om} * P_{a(n)}$
Replacement Cost	*Yr.(i)*		*PW*	
(i) Battery	5			$PW = C_{bat} * P_{r(i)}$
	10			
	15			
(ii) Charge controllers	5			$PW = C_{pc} * P_{r(i)}$
	10			
	15			
(iii) Power conditioner				$PW = C_{pc} * P_{r(i)}$
c) Life Cycle Replacement Cost	C_{rep}			
d) Salvage	C_{sal}			
4. Economic indicator				
Total Life Cycle Cost	LCC			LCC = a+b+c-d
Annualised LCC	ALCC			$ALCC = LCC/P_{a(n)}$
Cost of Electricity	COE			$COE = ALCC/L_a$

Appendix F : Nomenclature :

a , b	coefficients in empirical relationship
d	discount rate
f	frequency
h	height of panel, Plank's constant (chapter 2)
i	inflation rate
l	length of conductor
n	the number of days, period of analysis (chapter 4)
r	interest rate
t	time
C	cost of electricity
H	daily total radiation incident on a horizontal surface, height (chapter 4)
L	latitude angle
M	annual maintenance cost
N	day length or possible sunshine hours
M	minimum distance between row of panels, watts, width, weighting factor (chapter 4)
T	absolute temperature
A_a	effective area
A_p	panel area
A_s	area of power station
A_M	rated current of a module under STC
$AH_{(load)}$	daily energy of load required
C_{cap}	capital cost
C_i	capital cost of investment
$C_{O\&M}$	operation and maintenance cost
C_r	future cost
C_{rep}	replacement cost
C_{sal}	salvage cost
D_M	solar irradiation
D_y	solar irradiation throughout the year
E_b	size of battery capacity
E_d	total energy of daily load demand during daytime
E_n	total energy of daily load demand during night time
E_P	photon energy
E_{pv}	energy generated by the PV station
E_{sc}	solar constant
H_d	daily total diffuse radiation incident on a horizontal surface
H_o	daily extraterrestrial radiation incident on a horizontal surface
I_b	hourly beam radiation on a horizontal surface
I_d	hourly diffuse radiation on a horizontal surface
I_o	the radiation over a period of 1 hour, diode satiation current (chapter 2)
I_T	total hourly radiation on a tilted surface
I_{th}	total hourly radiation on a horizontal surface
K_T	daily clearness index
K_B	Boltzman's constant
N_A	total number of modules connected in a PV system
N_g	lightning flash density
N_p	number of panels
N_s	number of modules connected in series in a string
P_a	annual payment
P_o	output power of PV system at STC
P_y	yearly payment
R_b	ratio of beam radiation on a tilted surface to that on a horizontal surface
R_d	ratio of diffuse radiation on a tilted surface to that on a horizontal surface

R_g ratio of reflected radiation on a tilted surface to that on a horizontal surface
R_s series resistance of solar cell
R_{sh} shunt resistance of solar cell
T_{amb} maximum ambient temperature
T_M maximum operating cell temperature
V_B nominal battery bus voltage
V_D nominal battery discharge voltage
V_F forward voltage drop of blocking diode
V_{mp} voltage at maximum power point
V_w total wiring voltage drop
VF variability factor specified of climatic data

p_r single payment
r_d ratio of diffuse radiation in an hour to total in a day
r_t ratio of total radiation in an hour to total in a day

$\overline{H}$ monthly average daily total radiation incident on a horizontal surface
$\overline{H}_d$ monthly average daily diffuse radiation incident on a horizontal surface
$\overline{H}_o$ monthly average daily extraterrestrial radiation incident on a horizontal surface
$\overline{H}_B$ monthly average daily beam radiation on a tilted surface
$\overline{H}_D$ monthly average daily diffuse radiation on a tilted surface
$\overline{H}_G$ monthly average daily reflected radiation on a tilted surface
$\overline{H}_T$ monthly average daily total radiation on a tilted surface
$\overline{K}_T$ monthly average daily clearness index
$\overline{R}$ monthly average ratio of total radiation on a tilted surface to that on a horizontal surface
$\overline{R}_b$ monthly average ratio of beam radiation on a tilted surface to that on a horizontal surface

Greek :

α solar altitude angle, coefficient or rated cost for component (chapter 4)
β tilt angle, coefficient or area rated cost for land (chapter 4)
γ surface azimuth angle, power output coefficient (chapter 4)
δ declination of the sun
δ_w solar declination at the winter solstice
λ wavelength
ρ conductivity of cable
ω hour angle
ω_s sunset hour angle
ω_s' sunset hour angle for the tilted surface for mean day of the month
$\varnothing$ solar azimuth angle, solar radiation intensity (chapter 4)
θ incident angle, the angle between current and voltage (chapter 4)
θ_h incident angle on a horizontal surface
θ_t incident angle on a tilted surface
θ_z zenith angle
ε_o the eccentricity correction factor of the earth's orbit
ρ conductivity of copper
ρ_g ground reflectance for solar radiation
η yearly average efficiency
η_B battery efficiency
η_I inverter efficiency
η_L line loss factor
η_M module mismatch efficiency
η_R regulator efficiency
η_P panel efficiency

Appendix G

List of Publications

[1] S. Hiranvarodom, R. Hill and P. O'Keefe, A Strategic Model for PV Dissemination in Thailand, *Progress in Photovoltaics: Research and Applications*, **7**, 409-419 (1999).

[2] S. Hiranvarodom, R. Hill, P. O'Keefe and N. M. Pearsall, An Optional Design of PV Systems for a Thai Rural Village, *Proceeding of 16th European Photovoltaic Solar Energy Conference and Exhibition*, 1-5 May 2000, Glasgow, United Kingdom.